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DEVELOPMENTAL MECHANICS (*Entwicklungsmechanik*) is the name given in the 1890s by the German anatomist Wilhelm Roux to his experimental program for causal analysis of the transformation of fertilized eggs into multicellular organisms. More generally it also denotes the discipline of experimental embryology that flourished from the 1880s to the 1950s.

In France, Laurent Chabry was the first to apply the methods of experimental teratology—the mutilation of an embryo and comparison of its development to that of a normal embryo—to ascidian fertilized eggs. He built his own micro-tools to observe, manipulate, and kill a single blastomere (one of the segments formed by the division of the ovum) at the two-cell or four-cell stage. In his experiments he obtained half individuals or larvae with anomalies and concluded that each blastomere contained potential parts that were lost if destroyed. In Germany, Wilhelm His, who much improved research techniques by introducing serial microscopic sections, accepted descriptive embryology as essential for understanding the development of individual organs, but criticized its inability to reveal the factors responsible for differentiation. Chabry, His, and their colleagues criticized Ernst Haeckel for studying embryos only for the sake of establishing phylogenetic relationships, and mistrusted his so-called biogenetic law (ontogeny recapitulates phylogeny—the development of the individual follows that of the species).

Eduard Pflüger, professor of physiology at Breslau University, tested whether factors additional to ones internal to the fertilized egg directed development. In 1883, he analyzed the effects of gravitation on the cleavage of fertilized frog eggs and concluded that their development depended on external factors. Gustav Born and Roux, both then also working in Breslau, contested this interpretation. Roux refined Pflüger's experimental techniques and maintained that embryos developed normally even in altered environmental conditions, and that after the second cell division they were self-differentiating.

In 1888, Roux performed his celebrated experiment of puncturing one of the blastomeres of the frog's egg at the two-cell stage with a heated needle. Since in some cases the surviving blastomere developed into a well-formed hemi-embryo, Roux concluded that the experiment confirmed his theory of self-differentiation. According to Roux, every cell of a developing embryo has a capacity for self-determination that resided in the structure of the nucleus. He suggested that each cell division separated structurally differentiated nuclear material. He described the process as the production of a mosaic-work (mosaicism) in which each cell gives rise to different tissues and organs.

By shaking water containing sea urchin eggs, Hans Driesch separated the blastomeres from each other and dem-

embryos. Since these results contrasted with Roux's theory of self-differentiation by nuclear division, Driesch argued that the isolated blastomeres could produce all the parts of the organism by responding to the needs of the whole. Conflicting views over the interpretation of these experiments provoked a debate reminiscent of that between preformation and epigenesis in the eighteenth century. Roux's embryonic development was mechanistic and neo-preformationist, Driesch's vitalistic and neo-epigenetic.

Roux's research program acquired a commanding position in experimental embryology, which by innovating manipulative operations with extirpation, transplantation, and explantation techniques obtained astounding results usually published either in the *Archiv für Entwicklungsmechanik der Organismen,* a journal founded by Roux in 1893, or in the *Journal of Experimental Zoology.* The leading figures studying heredity and development at the cellular level were Theodor Boveri, Hans Spemann, Kurt Herbst, and Johannes Holtfreter in Germany; Charles Otis Whitman, Edmund Beecher Wilson, Thomas Hunt Morgan, Edwin Grant Conklin, Charles Manning Child, and Ross Granville Harrison in the United States; and Jean Eugène Bataillon and Etienne Wolff in France. Although experimental results did not give rise to a comprehensive theory concerning the transformation of a fertilized egg into a multicellular organism, they did clarify the external conditions necessary for development and showed that the factors guiding differentiation reside in the nucleus. Transplantation experiments in early embryos have shown the existence of organ-forming areas exhibiting various characteristics (Harrison's morphogenetic fields) and the capacity for integrated inductions of the upper lip of the blastopore (Spemann's organizer).

RENATO G. MAZZOLINI

DOUBLE HELIX. The double helix is the name associated with the molecular structure of deoxyribonucleic acid (DNA). Although isolated in the nineteenth century and identified chemically by 1909, its structure was not clarified until 1953 when Francis Crick and James D. Watson published their now famous model. The world authority on the nucleic acids, Phoebus Aaron Levene, had formulated the now infamous tetranucleotide structure, according to which the DNA molecule comprised four bases—adenine, guanine, cytosine, and thymine—attached to each other by a sugar-phosphate backbone. So small and boring a structure did not seem able to serve as a repository for the subtle and diverse specificities of the genetic material, yet DNA was long known to be the chief constituent of the chromosomes, the material bearers of our genes. Hence arose the suggestion that it acted as a "midwife" molecule assisting protein genes to duplicate. When in the 1940s it

Rosalind Franklin (1920–58), British X-ray crystallographer

rial viruses, DNA became a contender for the role of the genetic material.

Mounting an attack on the structure called for the skills of the X-ray crystallographer, good knowledge of chemistry, and much patience. The physical chemist Rosalind Franklin had all of these. When she took over the work on DNA at King's College London, she distinguished the crystalline A form and the wet B form, established the crystal parameters of the former, assigned it to its correct crystalline group (C2 monoclinic), and determined the change in length of the fibers in the transition from one form to the other. Her diffraction photograph of the B form in 1952 was stunning in its clarity and simplicity.

James D. Watson and Francis Crick were not officially working on DNA, but were so convinced of the importance of solving the structure and concerned that Franklin was going in the wrong direction, that they made two attempts on it themselves. Their first attempt failed. Their second, aided by knowledge of the contents of Franklin and Raymond Gosling's report to the Medical Research Council of December 1952, led to their famous double helical model. Unlike Franklin they had long been convinced that the DNA molecule is helical. Both also understood the potentially great biological significance of the structure.

Franklin told Watson and Crick that the sugar-phosphate backbone had to be on the outside. Her data suggested more than one helical strand. Crick realized that the symmetry of the crystalline A form indicated that the sugar-phosphate chains should run in opposite directions (anti-parallel). This proved to be a fundamentally important point in solving the structure. Watson solved the problem of putting the bases inside the helical cylinder of the two backbones by his innovation of the matching of the large purine bases (adenine and guanine) with the smaller pyrimidine bases (thymine and cytosine), so that adenine pairs with thymine and guanine with cytosine—another fundamental feature.

As refinements to the crystallographic data appeared, the double helix enjoyed growing support. Details were modified, but the basic structure has remained. Admittedly it was a shock when in 1959 the first single-crystal pictures of mixed nucleotides gave like-with-like pairing of the bases. Another seventeen years passed before data from single-crystal pictures supported the Watson-Crick scheme of pairing. A year later the non-helical "zipper" model was introduced as an alternative to the double helix. Not being a double helix, it could open out more easily for replication and transcription. But as we now know, nature long ago solved the problems associated with opening up the double helix.

Robert Olby

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EARLY HUMANS. The modern study of early humans depended on two major intellectual developments in the second half of the nineteenth century: rejection of the belief that human beings had existed only for the six thousand years of biblical time, and acceptance of the biological principle of human evolution. The major proponents of the antiquity of humans came from geology (Charles Lyell), paleontology (Hugh Falconer), and archaeology (John Lubbock and John Evans). Chance finds of flint tools predated the discovery of Brixham cave (1858), but the human-made artifacts and fossilized animal bones uncovered during its meticulous excavation proved conclusively that humans coexisted with extinct animals like mammoths of the late Pleistocene. The field methods of geology and relative dating using the fossil index had become a means to study our ancestors.

The comparative anatomy of great apes and humans provided evidence for human evolution. A committed Darwinian, T. H. Huxley argued in *Evidence as to Man's Place in Nature* (1863) for a common ancestor of humans and simians, and suggested searching for it in the fossil record. Some fossil discoveries, at Engis Cave, Belgium (1829), and Neander Valley, Germany (1856), predated the finds at Brixham. But the robustly built Neanderthal Man, with its prominent brow ridges, was often dismissed as a pathological aberration of a modern skeleton.

Gabriel de Mortillet organized the artifacts known in 1872 into a developmental sequence, an important improvement on the earlier systems of naming an object after the location where the "type specimen" was found. Mortillet's sequence overlay Édouard Lartet's for the Paleolithic based on supposedly predominant animal species. Edward B. Taylor and other anthropologists added a developmental perspective to studies of primitive societies, seeking observations of the "living Stone Age" in remote tribes. Further discoveries of Neanderthals in Europe, however, including almost complete skeletons at Spy, Belgium (1886), encouraged the search for fossils. Human paleontology (later paleoanthropology) thus became the dominant discipline in modern studies of early humans. While at first this work consisted of description and naming, the use of anthropomorphic measuring techniques (Aleš Hdrli ka) and later complex statistical analysis (William H. Howell) changed the search for type specimens into a much more dynamic endeavor.

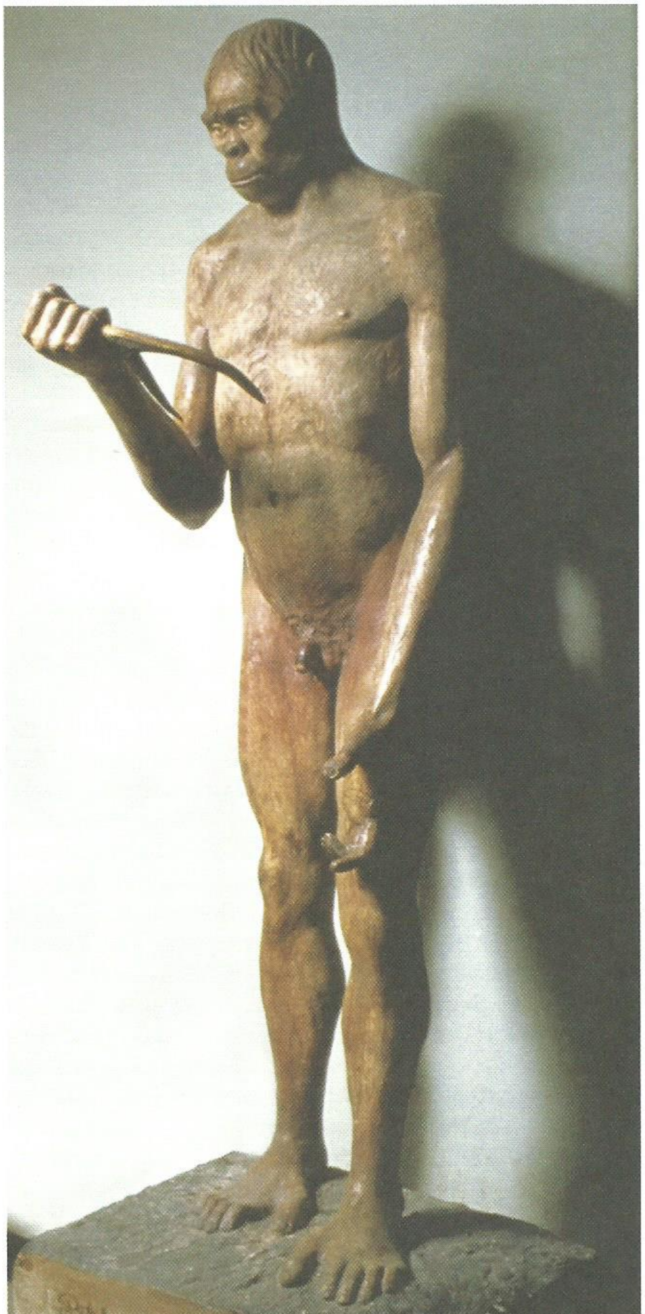
Ernst Haeckel championed the idea that fossils would provide evidence for the "missing link" between humans and other animals. He also believed that Asia had been the cradle of humankind. Inspired by his writings, the young Dutch doctor Eugèńe Dubois went to search in Java (now Indonesia) where, in 1891, he found a primitive skullcap. Further finds indicated that this hominid had walked upright. As with the Neanderthals, debate raged over the place of *Pithecanthropus erectus* in human evolution, but the notion of a large-brained, bipedal hominid ancestor received a strong fillip. Authors speculated for many years about the order in which the four main events purported to be essential for "humanness"—bipedalism, a large brain, descent from the trees, and tool-use/sociability/language—had occurred. Speculation had dangers, though. Grafton Elliot Smith, Arthur Smith Woodward, and Arthur Keith's belief in the primacy of a large brain led to their acceptance of the Piltdown fossil (1908), famously proved a hoax in 1953.

Marcellin Boule's analysis of the Neanderthal skeleton from La Chapelle-aux-Saints as brutish, shambling, and semiupright (1911–1913) unequivocally restored to this group its fossil status, but sidelined its ancestral role. The archaic modern fossil skeletons found at Cro-Magnon, France (1868), apparently provided a more acceptable forerunner for *Homo sapiens.* Boule championed the "pre-sapiens" theory, according to which a large-brained human ancestor with modern body proportions had been present as far back as the Pliocene. The ramifications of this idea resonated throughout the twentieth century. In South Africa (1924) the "Taung baby" *(Australopithecus africanus)*—a juvenile face and fossilized brain, about two million years old (myo)—was rejected by all save Raymond Dart and Robert Broom. It looked too apelike to belong in the human family. Moreover Asia was still the favored continent for human evolution despite Broom's finds of adult *Australopithecine* skulls in South African caves at Sterkfontein, Swartkrans, and Kromdraai. The Taung child was not accepted until the 1950s, after the exposure of Piltdown.

American vertebrate paleontologist Henry Fairfield Osborn continued to promote an Asian origin of the human family. He sponsored a series of expeditions to Central Asia. Davidson Black's later work (1927–1929) at Chou Kou Tien near Beijing, China, unearthed "Peking Man" (*Homo erectus*). Africa too had champions. In the 1920s, Louis Leakey returned to his native Kenya from Cambridge committed to the pre-sapiens theory, but with an African origin. Together with his second wife Mary, also an archaeologist, Leakey established the significance of Africa. Their son Richard took up the mantle with spectacular success in the latter half of the twentieth century, becoming with Donald Johanson one of the most celebrated "fossil hunters"—academics with a media profile, useful in funding increasingly complex and costly expeditions. The East African fossil finds—including "Zinj" (*Australopithecus boisei,* 1959), 1.7 myo; "1470" (*Homo habilis,* 1972), 1.9 myo; "Lucy" (*A. afarensis,* 1974), 3 myo; "the first family" (*A. afarensis,* 1975), 3 myo; "Homo erectus boy" (1984), 1.6 myo; "the black skull" (*A. aethiopicus,* 1985), 2.6 myo; and the preserved footprints of an upright hominid (1978), 3.5 to 3.7 myo—have extended our lineage back in time and suggested the coexistence of more than one species of hominids in Africa at intervals in the past. Charles Loring Brace and Milford Wolpoff in rehabilitating the Neanderthals argued that the same may be true in Europe and the Near East. The importance for paleoanthropology of thinking of populations as biological units, according to the new evolutionary synthesis launched by Ernst Mayr, Theodosius Dobzhansky, and George Gaylord Simpson in 1947, has become clear.

Increasingly sophisticated radiometric dating techniques have helped determine the absolute age of fossils. Computerized tomography scanners now allow paleontologists to see within fossils. Molecular biologists have suggested divergence dates based on similarities among human deoxyribonucleic acid (DNA) and mitochondrial DNA. An intellectual overhaul of archaeology, helped by Lewis Binford's view that we should not seek current behavior patterns in the historical record, turned attention away from the past search for "humanness." Allied with the rise of ecological thinking and general principles such as the effects of climate as an evolutionary lever, fossil hominids have been freed from the legacy of humans' once unique position in the natural order, to take their place in the changing environment of the planet's evolving ecosystem.

HELEN BYNUM



Full-size reconstruction of Java Man (*Pithecanthropus erectus*, later *Homo erectus*) by the Dutch anatomist Eugène Dubois (1858–1940) on the basis of fossil remains found in 1898

EARTH, AGE OF THE. Before the mid-eighteenth century, few scholars or scientists in the Christian West questioned the adequacy of the chronologies derived from the Mosaic narrative. They believed that the earth was little older than the few thousand years of recorded human history. Beginning in the second half of the eighteenth century, however, investigations of the earth's strata and fossils suggested that the earth's crust had undergone innumerable cycles of formation and decay and that it had supported an ever-changing sequence of living beings long before the first appearance of humans. For geologists such as James Hutton and Charles Lyell, the earth's age seemed too vast for human comprehension or measurement. By 1840, geologists had identified most of the major subdivisions of the stratigraphic column and arranged them in a chronological sequence, but it was a chronology without a measurable scale of duration, a history of the earth without dates.

In 1859, Charles Darwin attempted to determine one geological date by estimating how long it would take to erode a measured thickness of the earth's strata. His conclusion that 300 million years had been required to denude even the relatively recent strata of the Weald, a district of southern England, brought an immediate reaction. In 1860, the geologist John Phillips rebutted with an estimate that the composite thickness of the whole stratigraphic column could be denuded in only 100 million years. Soon afterward, the physicist William Thomson, Lord Kelvin calculated that 100 million years would be sufficient for the earth to cool from an assumed primordial molten condition to its present temperature. Kelvin's conclusions, based on the widely held hypothesis that the earth had been formed from the scattered particles of a primordial nebula, and supported by the latest theories of thermodynamics, carried great weight during the remainder of the century. Subsequent estimates of rates of erosion and sedimentation, of solar radiation and cooling, and of the time of formation of the Moon and the oceans converged on his figure of 100 million years.

All this was changed by the discovery in 1903 that radioactive elements constantly emit heat. A year later, Ernest Rutherford suggested that the ratio of the abundance of radioactive elements to their decay products provide a way to measure the ages of the rocks and minerals containing them. Robert John Strutt and his student, the geologist Arthur Holmes, pursued Rutherford's idea. By 1911, Holmes had used uranium/lead ratios to estimate the ages of several rocks from the ancient Precambrian period. One appeared to be 1,600 million years old. Many geologists were initially skeptical, but by 1930, largely as a result of the work of Holmes, most accepted radioactive dating as the only reliable means to determine the ages of rocks and of the earth itself. The discovery of isotopes in 1913, and the development of the modern mass spectrometer of the 1930s, greatly facilitated radioactive dating. By the late 1940s, the method produced an estimate of between 4,000 and 5,000 million years for the age of the earth. In 1956, the American geochemist Clare Cameron Patterson compared the isotopes of the earth's crust with those of five meteorites. On this basis, he decided that the earth and its meteorites had an age of about 4,550 million years. All subsequent estimates of the age of the earth have tended to confirm Patterson's conclusion.

JOE D. BURCHFIELD

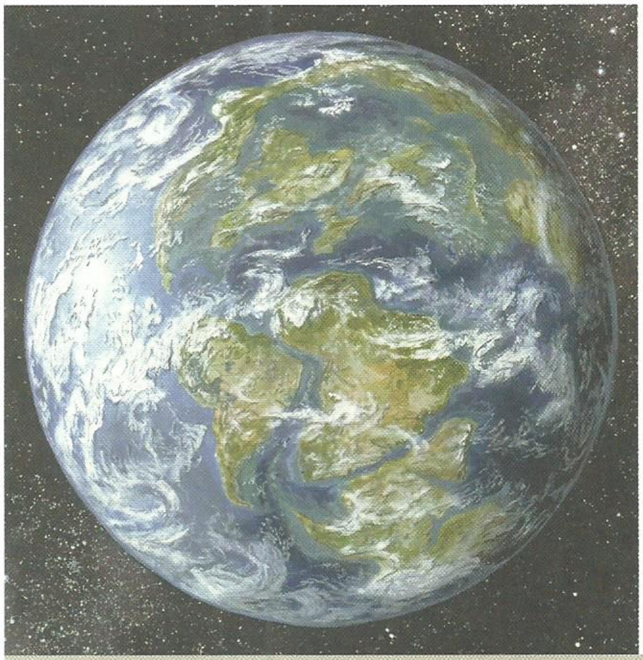
EARTH SCIENCE. The discipline of earth science was invented during the 1960s. It replaced geology as the major institutional framework for studying the earth just as geology had replaced mineralogy in the early nineteenth century. As with the simultaneous invention of planetary science, geologists had additional reasons for rethinking the status quo. Geology had lacked focus and exciting new ideas and techniques for the previous half century. Oceanographers and geophysicists had new instruments and techniques, particularly in submarine gravity studies, submarine seismology, deep ocean drilling and paleomagnetism.

The needs of submarine warfare during World War II and the Cold War gave a strong boost to seismology and studies of submarine gravity. Before World War II, the Dutch physicist Felix Andries Vening-Meinesz had developed a pendulum apparatus (now named after him) that made it possible to measure gravity at sea as accurately as on land. Using this apparatus, Vening-Meinesz and others mapped the gravity anomalies of the ocean floors and discovered the areas of downbuckling frequently associated with island arcs. Following the War, Maurice Ewing developed sea-floor seismic equipment, measured velocities in the sediments of the deep ocean, and contributed importantly to the understanding and detection of long range sound transmission in oceans.

In the late 1950s, the International Geophysical Year (IGY), which included gravity, geomagnetism, oceanography and seismology in its areas of concentration, further encouraged these lines of research. Deep ocean drilling that brought up cores from the sediments on the ocean floor began in the 1960s with the establishment of JOIDES (Joint Oceanographic Institutions for Deep Sea Drilling). At the same time, scientists at the United States Geological Survey, the University of Newcastle, and the Australian National University were racing to produce time scales of global magnetic reversals and theories of the motion of the magnetic north pole.

The promotion of the nascent discipline of earth science owed much to a few pioneering individuals and institutions. Among the individuals, in addition to those already mentioned, were J. Turzo Wilson, who led the Canadian contribution to the IGY and made major contributions to plate tectonics, and W. H. (Bill) Menard of Scripps Institution of Oceanography, later Director of the United States Geological Survey. The institutions that saw some of the important early work were spread across the English speaking world: Princeton University, Cambridge University, the University of Toronto, and the Australian National University, together with Lamont Doherty Geological Observatory (founded by Columbia University as a result of Ewing's successes) and Scripps Institution of Oceanography.

By the early 1970s, geophysicists, oceanographers, and geologists had pieced together the theory of plate tectonics. By the end of the decade, the theory had won worldwide acceptance, except in the Soviet Union. The theory vindicated the new approach to the science of the earth. It showed that expensive oceanographic surveys were necessary because the geology of the ocean floor turned out to be unexpectedly different from that of the land surface. It demonstrated that theorizing on a global scale led to the detection of patterns that would never have emerged from the laborious mapping of one square mile of the earth after another. And it showed once and for all that sophisticated instruments and high levels of funding need not be a waste of public money.



Artists concept of the position of Earth's continents about midway through the Cretaceous Period (136 to 165 million years ago). Africa and South America are shown before they split to form the Atlantic Ocean.

Simultaneous developments in other areas supported these conclusions. Geologists showed that the earth had suffered multiple impacts from meteors, asteroids, and other extraterrestrial bodies, ending the century-long convention that extraterrestrial phenomena were irrelevant to the study of the earth. When geologists found evidence supporting the thesis, put forward by Walter Alvarez, that one of these impacts precipitated the widespread extinctions at the Cretaceous-Tertiary boundary, the move to integrate earth and planetary science gained further momentum. The growing environmental movement and the popular belief that in some way all earth systems were interconnected doubtless also helped accelerate the shift to earth science.

During the 1970s and 1980s, established geology departments changed their names to earth science, or earth and ocean science, or earth and planetary science. They hired professors trained in physics and chemistry as well as in geology, and overhauled their curricula. Geological surveys rethought their missions, broadened their scope, and began using new instruments. The movement spread beyond research science. In 1982, a group of scientists founded the History of the Earth Sciences Society, and shortly thereafter began publishing *Earth Sciences History*, now the major journal for the history of geology and earth science. In 1983, the National Earth Science Teachers Association was chartered in the United States and began publishing *The Earth Scientist* to promote the teaching of earth science in the school system. Since the 1970s, instruments have continually improved. Magnetometers for measuring fossil magnetism which in the 1950s and 1960s were so new and intricate that many scientists believed the instruments created the effects observed by "paleomagicians" became standard, everyday, off-the-shelf tools. Theorizing has continued apace. Plate tectonic theory, which at first swept all before it, has been refined, and to some extent reformulated.

For all the success of earth science, traces of its roots in the formerly distinct areas of geology, geophysics, and oceanography remain. Major societies founded before the disciplinary transition, such as the American Association of Petroleum Geologists, the Geological Society of London, and the American Geophysical Union, still exist and continue to publish journals specializing in their traditional interests. And although histories of plate tectonics and biographies of its creators abound, as yet we have no comprehensive history of the disciplinary change to earth science.

RACHEL LAUDAN

ECOLOGY. In his groundbreaking 1927 textbook, *Animal Ecology,* Charles Elton characterized "ecology" as a new name for an old subject, or simply "scientific natural history." Much of ecology does concern phenomena that have been observed and pondered since antiquity, such as patterns in the geographical distribution of organisms, population fluctuations, predator-prey interactions, food chains, life cycles, and cycles of materials. Before the twentieth century, most of these phenomena fell within the domain of natural history. However, experts took up the many pieces of the subject in different studies in which the individual organisms, not their interrelationships, were the chief objects of study. The process by which the interrelationships themselves became the objects of study is the process by which ecology became a science.

The name came earlier than the science. In 1866 Ernst Haeckel coined the word "ecology," with more or less its current meaning, in a long treatise on animal morphology that owed much of its inspiration to Charles Darwin's theory of evolution. Haeckel wanted a name for a new branch of science that examined the collection of phenomena Darwin characterized as the "conditions of existence," that is, everything in the physical and biological environment of an organism that affects its survival in the broadest sense. Haeckel coined the term but did not make much use of it. The first to do so were botanists working during the 1890s mainly on the geographical distribution of plants. Although this line of research owed something to Darwin, it had deeper roots.

The leader of this older line of research, and one of Darwin's major sources of inspiration, was the German polymath Alexander von Humboldt, whose treatise on plant geography (or phytogeography), based upon a turn-of-the-century expedition to South America, became a model for the entire field. Humboldt's central contribution was to identify particular assemblages of plants, characterized by vegetation type, with particular environmental regimes. He divided the globe into discrete vegetation zones and made the observation, not unique to him, that the zones traversed in ascending high mountains, such as those he had climbed

Navy technicians check water pollution in the Arctic Ocean, Point Barrow, Alaska.

in the Andes, paralleled the zones passed through in traveling from the equator to the poles.

Over the course of the century, Humboldt's line of inquiry would be expanded, elaborated upon, and modified by a succession of European researchers. By the 1890s, a rich collection of observations and descriptions existed alongside a growing vocabulary of phytogeographical terms. This geographical tradition then meshed with a laboratory tradition, born in the revitalized and now thriving German university system, to produce detailed studies of plant adaptation under natural conditions—studies aided considerably by opportunities for travel opened up for European scientists as a result of intense colonization efforts in Asia and Africa and continued economic ventures in South America. In the United States, the maturation of the university system, combined with the expansion of the nation into the western regions of the North American continent, afforded similar opportunities for botanists. The science of ecology emerged out of this combined functional and geographical emphasis in botany around the turn of the century. North American botanists quietly adopted Haeckel's new term in 1893, and the Danish botanist Eugenius Warming published the first textbook to employ both the term and the concept in 1895.

With his knowledge of the laboratory methods taught in the German universities and his extensive travel experiences in South America and Europe, Warming developed his own classification scheme for plant communities based mainly upon available soil moisture in the habitats in which the characteristic plant groups are generally found. He also offered a discussion of ecological succession, the process by which different communities replace one another in the occupation of a particular site, such as a recently exposed rocky slope, a sand dune, or a burnt-over patch of forest. Warming's counterpart in Germany, Andreas Franz Wilhelm Schimper, in 1898 produced a similar textbook oriented toward plant geography, although with less emphasis on community structure. Schimper, to whom we owe the term "tropical rainforest," came from a school of laboratory-trained botanical field researchers who found more inspiration in Darwin's natural selection theory than did most early plant ecologists. Like many of his colleagues, Schimper traveled widely in the American tropics as well as in Germany's newly acquired Pacific island territories and the island of Java, where the Dutch colonial authorities maintained a botanical laboratory and garden. His textbook, like Warming's, provided a wealth of examples drawn from nature and became a source of inspiration for many budding ecologists in Europe and North America.

Meanwhile, young American botanists found ample opportunities for applying the latest insights and practices from European science to the study of North America's forests and grasslands, fast disappearing under the ax and the plow. A dynamic approach to plant ecology took shape, with emphasis on the process of succession and its inevitable culmination in the climatically determined "climax" community. This conception received its most thorough and persuasive treatment in the hands of Nebraska-born Frederic E. Clements, who spent most of his career in the western United States as a special ecological researcher for the Carnegie Institution. Although Clements's notion of "climax" came under attack at home and abroad, it nevertheless served as a productive focal point for the study of plant communities throughout the first half of the twentieth century. Clements's ideas found modest support among British plant ecologists, but numerous rival schools of plant ecology emerged in Germany, France, Switzerland, Scandinavia, and Russia, most of them promoting versions of what came to be known as phytosociology, or plant sociology—essentially the identification, often by elaborate sampling techniques and statistical methods, of natural plant groups associated with particular sets of environmental conditions. Whereas Clements and his followers focused on the climax community as the single, natural endpoint of a successional sequence, as well as a self-regulating, integrated whole, most European phytosociologists recognized multiple outcomes of successional sequences and did not necessarily emphasize the plant community as a stable, self-sustaining entity.

Studies of animal distribution began in the nineteenth century, but the formal development of animal ecology did not occur until the 1920s. British zoologist Charles Elton, whose field research emphasized the study of populations in the wild, was perhaps the most influential figure. Elton's work, often involving northern fur-bearing animals of commercial value, made a number of concepts part of the naturalist's vocabulary, including the ecological niche, the food chain, and the pyramid of numbers, that is, the decrease in numbers of individual organisms, or total quantity (weight) of organisms, at each successive stage in a food chain, from plants and plant-eating animals at the bottom to large carnivores at the top. Just as with plant ecology, diverse schools of animal ecology emerged in Europe and the United States during the first half of the twentieth century. Some schools, like Elton's, focused on empirical studies of predator-prey interactions and population fluctuations, others focused on animal community organization, still others on broader patterns of distribution and abundance.

Although some of the early work in animal ecology, particularly in the United States, attempted to model itself on plant ecology, by the 1930s animal ecology had emerged as an independent field. There was little overlap or interaction between the work of animal and plant ecologists. Effective impetus for an integrated perspective in ecology came from work in aquatic biology, best exemplified in the late nineteenth century by Karl Möbius's studies of the depleted oyster bank off Germany's north coast and the pioneering limnological (freshwater) studies of François Alphonse Forel on Swiss lakes. This work was continued and refined in the early twentieth century by many researchers, including August Thienemann in Germany and Einar Naumann in Sweden. Möbius's concept of the "biocenosis," the integrated community consisting of all living beings associated with a given habitat or a particular set of environmental conditions, was adopted widely by German and Russian ecologists in the 1920s and 1930s. An integrative perspective also emerged in soil science, as in Sergei Winogradsky's turn-of-the-century studies of soil microbiology, and in studies of biogeochemical cycles, as in the work of Russian geochemist Vladimir Vernadsky, who introduced the term "biosphere" in 1914. However, the integrative concept that had the broadest appeal and played a central role in bringing together the many different strands of ecological science was that of the "ecosystem," introduced by British botanist Arthur G. Tansley in 1935 but first used effectively in an aquatic setting.

Tansley was Britain's foremost plant ecologist and the founder in 1913 of the British Ecological Society, the first such national organization, formed two years earlier than its American counterpart. A pioneer in vegetation surveys, a critic of Clements's idea of the climax community, a passionate conservationist, and a student of Sigmund Freud, Tansley brought his broad experience and erudition to bear on the problem of identifying the ideal ecological unit of study. He suggested that the term "ecosystem" captured this concept best without implying any mysterious vital properties. The new term received its fullest early treatment in a seminal paper published in 1942 by a young American limnologist, Raymond Lindeman. Making use of the concept of ecological succession, Elton's pyramid of numbers and food chains, earlier studies of energy flow in aquatic systems, and Clements's notion of the stable climax community, Lindeman traced the flow of energy through the different trophic (feeding) levels (producers, primary consumers, secondary consumers) in a small Minnesota pond as a way to map its structure as an ecosystem and to demonstrate its progress in development toward a stable, equilibrium state.

World War II proved to be a watershed for ecology. Although earlier preoccupations with community classification and structure, population dynamics, and patterns of distribution continued in the postwar years, newer methodologies, practices, and conceptual schemes took hold, and ecology as a science and a profession grew in size, status, and organization. In the postwar period, Lindeman's groundbreaking work on ecosystem ecology found a home among biologists funded by the U.S. Atomic Energy Commission, who used radionuclides to trace the flow of materials and energy through natural ecosytems. Ecosystem research soon expanded from its base in the Atomic Energy Commission. It also prospered among a small group of Tansley's followers at the new Nature Conservancy in Britain. It became an essential feature of modern ecological science, a message conveyed to several generations of students worldwide through the successive editions of Eugene P. Odum's *Introduction to Ecology,* first published in 1953. Meanwhile, the prewar synthesis of Darwinian natural selection theory with Mendelian genetics resulted in the gradual postwar emergence of a more strongly Darwinian perspective in population and community ecology.

The postwar years also saw a shift toward quantitative aspects of ecology. Mathematical techniques developed in the United States, Europe, and the Soviet Union during the interwar period joined with war-born techniques involving information systems and cybernetics to produce a movement toward mathematical modeling and computer simulation of populations, communities, and ecosystems. Much of this modeling and its techniques came under attack during the last decades of the twentieth century. Some ecologists abandoned model building for empirical studies, others worked on refining and improving the models, and many called into question the underlying notions of stability and equilibrium upon which most of the models were based.

The devastation brought by World War II also contributed to greater postwar interest in the conservation of natural resources, protection of wildlife, and preservation of natural environments, a trend that, when linked in the 1960s with social criticism, blossomed into an international environmental movement that drew heavily upon concepts and theories of ecology. As had occurred before the war in a more limited way among a few visionaries, ecology now came to be widely viewed not only as the source of remedies for environmental ills but also as the scientific underpinning for a new social order. This proved to be a mixed blessing for ecologists. On the one hand, funding for ecological research increased considerably, and many more people were drawn into the field. On the other hand, the theoretical framework of ecological science, being neither unified nor consistent, could not provide easy, unambiguous solutions to environmental problems, let alone unified and consistent social visions. Toward the end of the twentieth century, this disagreement and uncertainty among ecologists was used as fuel in legislative and legal debates arguing against the protection of endangered species and the maintenance of pristine nature reserves. This situation encouraged the further refinement and integration of ecological science toward the incorporation of human disturbance and the notion of managed ecosystems.

EUGENE CITTADINO

ELECTRICITY was originally the term used to describe the power acquired by certain substances, notably amber, when rubbed, to attract nearby small objects. This power, known to the Greeks, was carefully distinguished by William Gilbert (1600) from magnetism. Seventeenth-century philosophers were unanimous in believing that the rubbing agitated a subtle matter associated with ordinary matter, causing it to be ejected into the surrounding air, where it (or perhaps air rushing in to fill the space left empty) swept up any light objects in the way.

Francis Hauksbee (c. 1666–1713) obtained more powerful effects by mounting a glass globe on a spindle and rubbing it as it rotated. He showed that electrification was linked to the emission of light—indeed, in Hauksbee's experiments it seemed that the subtle matter streaming from electrified bodies could be felt, seen, and heard. As elaborated by Jean-Antoine Nollet in the 1740s, the theory envisaged fiery matter streaming from electrified bodies, while other streams flowed in to replace the matter that had left.

In 1731, Stephen Gray discovered that the electrical attracting power could be transmitted over great distances, provided that the conducting line was made of an appropriate material and suitably supported. This led to a distinction between "electrics"—substances electrifiable by friction but poor conductors—and "non-electrics"—substances not electrifiable by friction but good conductors.

In 1746, Petrus van Musschenbroek announced a sensational discovery, the "Leyden experiment," in which a bottle filled with water and electrified by means of a conductor leading from a generating machine into the water delivered a terrible blow when contact was made simultaneously with the conductor dipping into the water and the outer surface of the bottle. "I thought it was all up with me," Musschenbroek reported. Enthusiasts everywhere rushed to repeat the experiment. Nollet delighted the French king by discharging a bottle through a line of monks, making them leap into the air simultaneously. In America, Benjamin Franklin and his friends amused themselves with electrical party tricks.

Franklin also devised a new theory of electricity that in time became generally accepted. He, too, supposed that ordinary matter was suffused with subtle fluid. For Franklin, however, electrification consisted in the redistribution of this fluid between rubber and rubbed, one finishing up with more than its natural quantity, the other with less. The notion of electrical "charge" thus acquired a meaning, the bodies becoming electrified "plus" and "minus" respectively. Noting the ability of pointed conductors to discharge nearby charged objects, Franklin conceived an experiment, first successfully performed near Paris in May 1752, to demonstrate that thunderclouds were electrified and lightning was an electrical discharge. His conclusion that erecting pointed conductors (lightning rods) on buildings could protect them from lightning strikes was hailed as a triumph of reason over nature.

A fanciful painting of Alessandro Volta showing his electric battery to Napoleon Bonaparte (seated) and other men of science in Paris in 1800

Franklin's theory worked well in explaining when a shock would be experienced in a variety of situations. He did not provide a coherent dynamical basis for his theory. In 1759, Franz Ulrich Theodosius Aepinus published a fully consistent version of Franklin's theory, based explicitly on forces acting at a distance between particles, whether of fluid or of matter. By adding the forces acting in various situations, he gave satisfactory explanations for a wide range of effects, and successfully predicted others. His ideas were taken up by leading investigators of the next generation such as Alessandro Volta and Charles Augustin Coulomb, who showed in 1785 that the forces involved obeyed an inverse-square law with respect to distance. On this basis, Simeon-Denis Poisson developed a full mathematical theory of electrostatics in 1812.

To make his theory consistent with elementary observation, Aepinus found it necessary to assume that particles of ordinary matter repelled each other. Many people rejected this idea, supposing instead the existence of two electric fluids that normally neutralized each other but that became separated in electrification. This theory attributed to the second electric fluid the additional repulsive force that Aepinus invoked. Operationally, the one-fluid and two-fluid theories could not be distinguished, and each found adherents.

In the 1790s, controversy erupted between Alessandro Volta and Luigi Galvani over Galvani's experiments in which frogs' legs jerked spasmodically when a conducting circuit was completed between the crural nerve and the leg muscle. Galvani attributed the effect to the discharge of "animal electricity" accumulated in the muscle, which he saw as analogous to a Leyden jar. Volta believed the cause was ordinary electricity, and concluded that dissimilar conductors in contact generate an electromotive force. He built a "pile" comprising pairs of silver and zinc disks separated by pieces of moist cardboard, the electrical force of which he managed to detect with a sensitive electroscope.

Volta's device was the first source of continuous electric current. Its operation was accompanied by chemical dissociations within the moist conductor and in any other conducting solutions forming part of the electrical circuit. These became a focus of research, leading to Humphry Davy's successful isolation of potassium and sodium in 1807 by electrolyzing molten potash and soda, respectively, and eventually to large-scale industrial applications of electrochemical processes.

In 1820, Hans Christian Oersted discovered that a wire carrying an electric current deflects a magnetic needle. André-Marie Ampère quickly showed that a current-carrying loop or solenoid was equivalent to a magnet, and proposed that all magnetism arose from solenoidal electric currents in molecules of iron. Ampère's discovery led to the construction of electromagnets—iron-cored solenoids carrying ever-larger currents—that produced magnetic effects far more powerful than any previously known. Then, in 1831, Michael Faraday discovered electromagnetic induction: when an electrical conductor cuts across lines of force, an electromotive force is generated in the conductor. These discoveries underpinned the development, first, of the electric telegraph and, later in the nineteenth century, the electrical power industry, which provided a continuous supply of electrical power for industrial or domestic use from generators in which coils of conducting wire placed between the poles of a powerful electromagnet were rotated by steam or water pressure. In the twentieth century, the increasing availability of such power, and the rapid proliferation of appliances to exploit it, transformed civilized life.

But what is electricity? For most nineteenth-century physicists, sources of electromotive force literally drove a current of the electric fluid (or fluids) around a conducting circuit. In an electrolytic cell, the electrodes acted as poles, attracting the constituent parts of the solute into which they were dipped. For Faraday, however, and later for James Clerk Maxwell, the energy resided not in electrified bodies but in the medium surrounding them, which was thrown into a state of strain by the presence of a source of electromotive force. If the medium were a conductor, the tension would collapse, only to be immediately restored; the product of this continuous repetition, the "current," was a shock wave propagated down the conductor. Static electric charges represented the ends of lines of unrelieved electric tension.

These ideas were widely influential in late-nineteenth-century physics, even though they left the relationship between electricity and matter far from clear. Following the discovery of the electron by Joseph John Thomson in 1897, however, and the recognition that it was a universal constituent of matter, electric currents again came to be conceived in terms of a flow of "subtle fluid"—now clouds of electrons semidetached from their parent atoms, driven along by an electromotive force. No longer, however, was "charge" defined in terms of accumulations or deficits of this fluid. Rather, charge became a primitive term, a quality attributed to the fundamental constituents of matter that was itself left unexplained. Some kinds of fundamental particles, including electrons, carry negative charge, whatever that might be, whereas others carry an equally mysterious positive charge: in combination, these two kinds of charge negate each other. After Robert Millikan's experiments (1913), most physicists accepted the notion that there is a natural unit of electricity, equal to the charge on the electron. The current standard model in elementary particle physics, however, assumes the existence of sub-nucleonic constituents ("quarks") bearing either one-third or two-thirds of the unit charge. Neither these quarks nor their fractional charges have been detected in a free state.

R. W. HOME

The Danish natural philosopher Hans Christian Oersted (1777–1851) apparently thinking about possible interactions between electricity (generated by Volta's battery) and magnetism (detected by a compass needle)

ELECTROMAGNETISM. The study of electricity and magnetism has alternated between theories that represented the two as manifestations of a single effect and the view that they were separate phenomena, with general inflection points around 1600 (when the two fields were divided) and 1820 (when they reunited).

Ancient and medieval philosophers did not distinguish between the ability of amber to attract objects and the action of the lodestone on iron. In 1600, William Gilbert insisted on a distinction between the two, coining the term "electricity" to describe the effect of amber and attributing it to many other substances; the lodestone remained for Gilbert the sole source of magnetism, around whose force he constructed an entire cosmology. Gilbert's successors spent the seventeenth century searching for the source of electrical and magnetic phenomena and generally finding it in material emanations, such as René Descartes's theory of magnetic effluvia that swarmed around iron and accounted for magnetic action.

Over the course of the eighteenth century, natural philosophers incorporated the distinct fields of electricity and magnetism within a new quantitative, experimental discipline of physics, aided by new instruments to produce phenomena—electrostatic machines like Francis Hauks-bee's spinning glass globe, and the Leyden jar, an early form of capacitor—and to measure them, such as the electroscope, which indicated electrical force by the displacement of threads, straws, or gold leaf. Quantification allowed mathematicians, notably Henry Cavendish and Charles Augustin Coulomb, to follow Isaac Newton's example for gravitation and reduce electro- and magnetostatics to distance forces. Philosophers around 1800 explained their measurements in terms of a system of imponderable fluids, with one (or two) weightless, elastic fluid(s) each for electrical and magnetic forces. But despite similar mathematical and conceptual approaches to electricity and magnetism, the phenomena still appeared unrelated. Electricity produced violent action like lightning or sparks, unlike milder magnetic effects, and did not have the same polar behavior.

One of the new instruments, Alessandro Volta's battery, produced a flow of current electricity. It thus enabled the unification, or reunification, of electricity and magnetism, whose interactions stemmed from dynamic electric and magnetic effects. In 1820, Hans Christian Oersted noticed that a current-carrying wire displaced a nearby compass needle. Oersted's response reflected his adherence to Naturphilosophie, a metaphysical system advanced at the time by German philosophers who sought single polar forces underlying various domains of natural phenomena. Oersted thought his experiment gave evidence of such a unifying force and proposed a connection between electricity and magnetism. André-Marie Ampère soon mathematized Oersted's experiment, providing a force law for currents in wires. In 1831, Michael Faraday, who may also have dabbled in Naturphilosophie, explored the reverse effect, the ability of a moving magnet to generate electric currents. Oersted, Ampère, and Faraday thus established electromagnetism, although all three noted a difference between the linear action of electricity and the circular action of magnetism.

Faraday formulated the concept of fields to explain the action of electric and magnetic forces at a distance. Instead of material, if weightless, fluids carrying the force, Faraday attributed the source of electromagnetic action to lines of force in the medium between currents and magnets: lines of force ran from one magnetic pole to the opposite pole, and between opposite electrical charges; magnets or conductors experienced pushes or pulls as their motion intersected these lines of force. James Clerk Maxwell in the 1860s and 1870s systematized the field concept and the interaction of electric and magnetic forces in a set of differential equations, later simplified into four basic equations. Maxwell's theory, which interpreted light as very rapidly oscillating electric and magnetic fields, received experimental confirmation by Heinrich Hertz, who starting in 1887 demonstrated the propagation of electromagnetic waves through space.

Over the course of the nineteenth century, experimental work on electromagnetism, especially in Germany, spurred the emergence of precision physics, which in turn promoted the establishment of academic research institutes. Electromagnetism provided one of the two main lines of development of nineteenth-century physics, along with thermodynamics and the kinetic theory. Whereas thermodynamics derived from the first industrial revolution of the late eighteenth century, specifically the program to describe the working of the steam engine, electromagnetism stimulated the second industrial revolution of the late nineteenth century.

Electromagnetism gave rise to industries around the telegraph, a result of Oersted's discovery of mechanical motion produced by electric current; electric power generation and transmission, with the dynamo deriving from Faraday's work on the transformation of mechanical motion into electric current; and radio, a consequence of Hertz's experiments on the free propagation of electromagnetic radiation. Together with chemistry and the chemical industry, electromagnetism and its applications exemplified the science-based industry of the second industrial revolution. But the electrical industry did not just apply scientific theories developed in isolation from commercial concerns; rather, prominent scientists, such as William Thomson (later Lord Kelvin) and Oliver Heaviside tackled practical problems, especially in telegraphy, and thus advanced the state of electromagnetic theory.

Since Maxwell's theory established a conception of light as a form of electromagnetic waves, electromagnetism merged with theoretical optics. At the end of the century, some physicists sought to extend the domain of electromagnetism to all physical phenomena, including mechanics and gravity, in what was called the electromagnetic worldview. Many electromagnetic theories relied on an all-pervasive ether as the medium for electromagnetic waves. Albert Einstein's theory of relativity at the outset of the twentieth century enshrined the interchangeability of electrical and magnetic forces and banished the ether, leaving electromagnetic waves to propagate through empty space at the speed of light. The concurrent development of quantum theory, which itself arose from the application of thermodynamics to electromagnetic waves (in the form of heat radiation), led to the wave-particle duality, in which electromagnetic radiation at high frequencies may behave either as a wave or a particle. The elaboration of quantum electrodynamics starting around 1930 provided a quantum theory of electromagnetism and a description of the duality.

Physicists later in the twentieth century came to view electromagnetism as one of four fundamental forces, the others being gravity and the strong and weak nuclear forces. Particle physicists hoped to show that each force was a particular manifestation of a more general force; they thus joined the unified electromagnetism with the weak (in the so-called electroweak force) and then the strong force (in quantum chromodynamics), and sought in vain for final unification with gravity in a so-called theory of everything.

PETER J. WESTWICK

ELECTROTECHNOLOGY. The first practical (and very questionable) application of electricity occurred in the eighteenth century. Using electrostatic machines and Leyden jars, natural philosophers, doctors, and various charlatans administered sparks to paralytics and otherwise tried to repair the body by shocks and effluvia. Another early example of electrical technology, the lightning conductor, was comparatively reliable. Alessandro Volta's invention of the electrochemical cell or battery grandly enlarged the range of application of electricity. The battery's current could produce electrolysis, generate a bright light across a gap between two carbons, and act upon a magnet. Michael Faraday's discovery that the relative movement of wires and magnets induce electric currents made motors possible. But the very first electromagnets, electric motors, generators, and lamps were little more than scientific toys, at home only in laboratories and in lecture rooms. Also, despite countless improvements introduced after Volta, the battery remained an inefficient and expensive source of energy. The first electric motors could not compete with steam engines. Electric arc lights, too bright for domestic application and requiring a complex regulating apparatus, were confined to lighthouses until technical improvements suited them for public buildings and street illumination in the later decades of the nineteenth century.

The first successful practical applications of electricity were electroplating and electric telegraphy in the 1840s. Around the beginning of the decade, an electrochemical process was discovered for depositing a thin layer of gold or silver on a non-noble metal (or a conductive mould made of graphite-covered gutta-percha). Electroplating and electroforming permitted the bulk production of inexpensive "artistic objects" for the growing middle class. Decoratively wrought metal objects (cutlery, vases, statuettes, candlesticks), previously manufactured only in limited numbers by skillful craftsmen, could be multiplied cheaply and accurately.

Telegraphy also boomed in the 1840s, the development of transmission lines accompanying the growth of national railroad systems. In the second half of the nineteenth century, entrepreneurs pressed the creation of an international telegraphic network that demanded an unprecedented effort from physicists, engineers, and electrical manufacturers. New materials (e.g., for insulating cables) had to be developed, and measuring instruments refined. New technologies for making and laying underwater cable had to be invented. Universal electrical standards were needed to allow interconnection of apparatus of diverse origins into a world network; new apparatus was required for detecting the weak signals traveling over thousands of miles. The scientific and technical community, industrialists, tycoons, and politicians joined their efforts for the achievement of this global enterprise. The first transatlantic cables were laid in the 1860s with physicist William Thomson, Lord Kelvin, in charge of testing the cable as it paid out.

The telegraphic industry supported many spin-offs and trained many inventors of electrical devices. Pantelegraphy, invented by the Italian Giovanni Caselli in the late 1850s, a primitive form of fax, allowed transmission of images by telegraph. It was deployed in France during the Second Empire, but the market was too small to sustain it after 1870. At the turn of the century, however, electric transmission of static images returned (with a better technology) to supply newspapers and magazines with photographs from around the world. Thomas Edison got his start as a telegraphist; his contributions to the field, such as the stock ticker, laid the groundwork for a number of his later inventions, including the phonograph.

In the late 1860s, a number of inventors and scientists with telegraphic experience, notably Charles Wheatstone and Ernst Werner von Siemens, introduced the first self-excited generators, far more powerful and efficient than earlier models. Another major step, taken by the Italian physicist Antonio Pacinotti in the 1860s, was a reversible dynamo machine, an ideal prototype for a direct current electric motor and generator. Pacinotti did not find a favorable industrial environment in Italy and tried to commercialize his apparatus abroad. In 1869, the Belgian Zénobe-Théophile Gramme, a skilled mechanician, transformed "Pacinotti's ring" into an industrial product. With better generators and motors electricity could be used not only for arc lighting, which gained ground in the 1870s, but also for mechanical power.

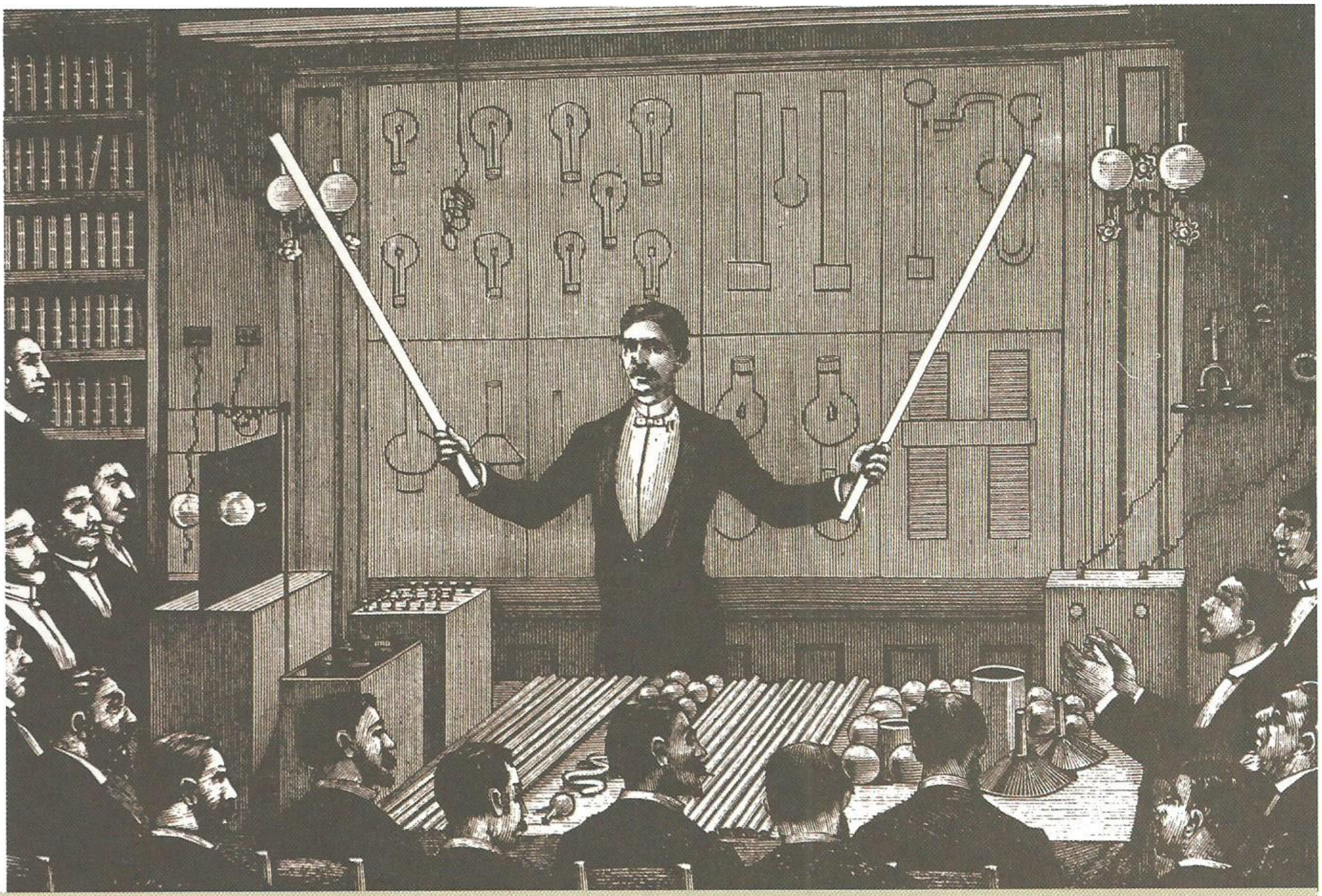
During the last decades of the nineteenth century several inventors proposed types of incandescent lamps to challenge gas and oil illumination. The new lamps required a complex system of generators, cables, switches, electricity meters, fuses, and lamps. Edison developed the first commercially successful system in the early 1880s—a triumph based not only on technology, but clever advertising and lobbying as well.

Supplying electricity was one thing, metering it another. The standard laboratory instruments were too delicate and temperamental for extended use in factories and power plants. In the 1880s the American electrical engineer Edward Weston patented a series of solid, reliable voltmeters and ammeters easy for unskilled workers to use. Weston's measuring instruments proved to be so well designed that they were used with few modifications for more than a century.

In 1885, both the Italian physicist and engineer Galileo Ferraris and the Serbian-born American electrician Nikola Tesla discovered the principle of the rotating magnetic field and the induction motor. Ferraris, a university professor, did not care to develop his discovery industrially and built only a few pieces of demonstration apparatus. Tesla, an inventor, patented various types of motors and generators and laid down the principles of modern polyphase electrical systems, which the industrialist George Westinghouse exploited. The alternating-current system met with fierce opposition from the supporters of the existing direct-current technology. The subsequent "battle of the currents" turned more on economic and industrial strategies than on scientific arguments.

In 1888, physics professor Heinrich Hertz demonstrated the existence of the electromagnetic waves deducible from James Clerk Maxwell's equations. For several years these radio waves remained a lecture demonstration. Pioneers of wireless such as Oliver Joseph Lodge and Guglielmo Marconi faced the problem of detecting the waves over distances wider than lecture halls and transforming successful technology into a reliable commercial system. At the end of the nineteenth century, wave propagation was still mysterious; no one understood fully how antennas and detectors worked and the invention and improvement of wave detectors depended more on empirical trial and error, practical savoir-faire, and technical skill than on scientific research. Wireless experimenters advanced in an almost virgin field, or rather forest, and their work opened new perspectives to scientific research.

In the twentieth century, the booming electrical (and later electronic) industry increased demand for systematic



Nicola Tesla (1856–1943) entertaining electricians ca. 1900 research and development. The growing complexity, variety, and cost of apparatus, components, networks, and systems, necessitated rational planning. Industries developed their own research and development units. The boundary between laboratory research and workshop activity became even vaguer. Science tended increasingly toward industrialization and industry toward subordination to science.

PAOLO BRENNI

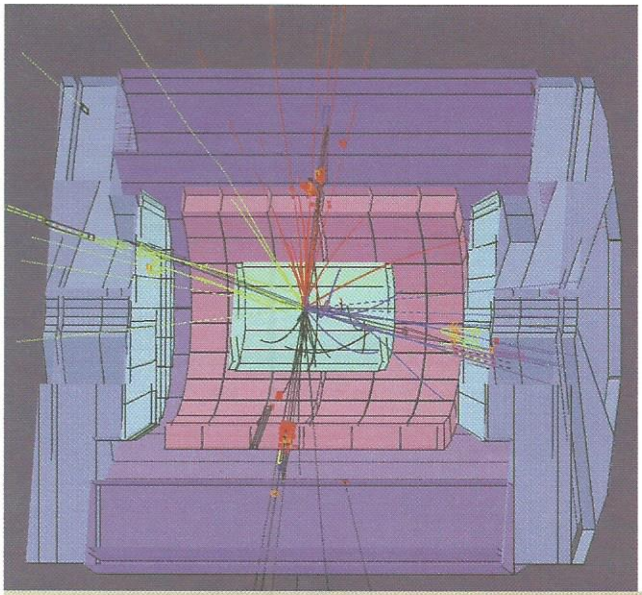
ELEMENTARY PARTICLES. Modern particle physics began with the end of World War II. Peace and the Cold War ushered in an era of new accelerators of ever increasing energy and intensity able to produce the particles that populate the subnuclear world. Simultaneously, particle detectors of ever increasing complexity and sensitivity recorded the imprints of high-energy subnuclear collisions. Challenges, opportunities, and resources attracted practitioners: the number of "high energy" physicists worldwide grew from a few hundred after World War II to some 8,000 in the early 1990s.

Developments in 1947 shaped the further evolution of particle physics. Experimental results regarding the decay of mesons observed at sea level presented to the Shelter Island conference led Robert Marshak to suggest that there existed two kinds of mesons. He identified the heavier one, the π meson, with the meson copiously produced in the upper atmosphere in nuclear collisions of cosmic-ray particles with atmospheric atoms and with the Yukawa particle responsible for nuclear forces. The lighter one, the μ meson observed at sea level, was the decay product of a π meson and interacted but weakly with matter. A similar suggestion had been made earlier by Shoichi Sakata in Japan. Within a year, Wilson Powell identified tracks showing the decay of a π into a μ meson in a nuclear emulsion sent aloft in a high altitude balloon. During the early 1950s the data obtained from particles produced in accelerators led to the rapid determination of the characteristic properties of the three varieties of π mesons.

The two-meson hypothesis suggested amendments to the list of particles. Some particles ("lep-tons")—the electron, muon, and neutrino—do not experience the strong nuclear forces. Others ("hadrons")—the neutron, proton, and the π-mesons do interact strongly with one another. It proved useful to split the hadrons into baryons and mesons. Baryons, of which the proton and neutron are the lightest representatives, have odd-half integer spin and (except for the proton) are unstable, one of the decay products always being a proton. Mesons have integer spin and when free ultimately decay into leptons or photons.

In January 1949, Jack Steinberger gave evidence that the μ-meson decays into an electron and two neutrinos, and shortly thereafter several theorists indicated that the process could be described in the same manner as an ordinary β-decay. Moreover, they pointed out that the coupling constant for this interaction had roughly the same magnitude as the constant in nuclear β-decay. Attempts then were made to extend an idea Oskar Klein had put forth in 1938, that a spin 1 particle, the "W boson," mediated the weak interactions and that the weakness of the β-decay interaction could be explained by making the W mesons sufficiently heavy.

During the first half of the 1950s theoretical attempts to explain pion-nucleon scattering and the nuclear forces were based on field theoretical models emulating quantum electrodynamics (QED). The success of QED rested on the validity of perturbative expansions in powers of the coupling constant, $e^2/hc = 1/137$. However, for the meson theory of the pion-nucleon interaction the coupling constant had to be large—around 15—to yield nuclear potentials that would bind the deuteron. No one found a valid method to deal with such strong couplings. By the end of the 1950s quantum field theory (QFT) faced a crisis because of its inability to describe the strong interactions and the impossibility of solving any of the realistic models that had been proposed to explain the dynamics of hadrons. Theorists abandoned efforts to develop a theory of the strong interactions along the model of QED, although Chen Ning Yang and Robert L. Mills advanced a local gauge theory of isotopic spin symmetry in 1954 that proved influential later on. Local gauge invariance, however, implies that the gauge bosons are massless. This is not the case for the pion and thus Yang and Mills's theory was considered an interesting model but not relevant for understanding the strong interactions.



Computer graphic of the first creation of W particles at CERN in 1996 by a collision between a proton and an antiproton. Each W decays into a quark and an antiquark, which give rise to the four sprays of particles shown in pink, purple, and blue.

The crisis in theoretical particle physics at the end of the 1950s inspired several responses. It led to the explorations of the generic properties of QFT when only such general principles as causality, the conservation of probability (unitarity), and relativistic invariance figured and no specific assumptions regarding the form of the interactions were made. Geoffrey Chew's *S*-matrix program that rejected QFT and attempted to formulate a theory that made use only of observables was more radical.

Another response to the crisis made symmetry concepts central. First applied to the weak and the electromagnetic interactions of the hadrons, symmetry considerations were later extended to encompass low-energy strong interactions. Symmetry became one of the fundamental concepts of modern particle physics, used as a classificatory and organizing tool and as a foundational principle to describe dynamics. Interest in field theories, and in particular in gauge theories, revived after theorists had appreciated the notion of spontaneous symmetry breaking (SSB). SSB allows a field theory to have a much richer underlying symmetry than that observed. Usually a symmetry expresses itself in such a way that the vacuum state of the theory is invariant under the symmetry that leaves the description of the dynamics (the Lagrangian) invariant. In the early 1960s, Julian Schwinger, Jeffrey Goldstone, Yoichiro Nambu, Steven Weinberg, Abdus Salam, and others noted that in quantum field theories symmetries could be realized differently: the Lagrangian could be invariant under some symmetry, without the symmetry applying to the ground state of the theory. Such symmetries are called "spontaneously broken" (SBS).

In 1967 Weinberg, and in 1968 Salam, independently proposed a gauge theory of the weak interactions that unified the electromagnetic and the weak interactions and made use of the Higgs mechanism, which generates the masses of the particles associated with the gauge theory. Their model incorporated previous suggestions by Sheldon Glashow (1961) for formulating a gauge theory in which the gauge bosons mediated weak forces. The renormalizability of such theories—the existence of consistent algorithms for extracting finite contributions from every order of perturbation theory—was proved by Gerard 't Hooft in his dissertation in 1972. The status of the Glashow-Weinberg-Salam theory changed dramatically in consequence. As Sidney Cole-man noted in his article in *Science* describing the award of the Nobel Prize to Glashow, Salam, and Weinberg in 1978, "'t Hooft's kiss transformed Weinberg's frog into an enchanted prince."

As presently described, a common mechanism underlies the strong, weak, and electromagnetic interactions. Each is mediated by the exchange of a spin 1 gauge boson. The gauge bosons of the strong interactions are called gluons, those of the weak interactions, $W^\pm$ and Z bosons, and those of electromagnetism, photons. The charges are often called "colors": QED, the paradigmatic gauge theory, works with a single gauge boson, the photon, coupled to a single "color," namely the electric charge. The gauge bosons of the strong interactions carry a three-valued color, those of the weak interactions carry a "two-dimensional" weak color charge. Weak gauge bosons interact with quarks and leptons and some of them, when emitted or absorbed, can transform one kind of quark or lepton into another. When these gauge bosons are exchanged between leptons and quarks they are responsible for the force between them. They can also be emitted as radiation when the quarks or leptons accelerate.

Quantum chromodynamics (QCD) describes the strong interactions between the six quarks: the up and the down, the charmed and the strange, and the top and the bottom. They are usually denoted by u, d, c, s, t and b. Evidence for the top quark was advanced in the fall of 1994 and confirmed in the spring of 1995. Quarks carry electrical charge and in addition a "three dimensional" strong color charge. QCD is a gauge theory with three colors, eight massless gluons, and color-carrying gauge bosons, six that alter color and two that merely react to it. Gluons do not carry color in the same way as quarks do; they carry a color-anticolor, which enables them to interact with one another.

In QFT the vacuum is a dynamic entity. Within any small volume of space-time the root mean square values of the field strengths (electric and magnetic in QED, color-gluon field in QCD) averaged over the volume do not vanish. Virtual particle-antiparticle pairs are constantly being created, and as demanded by the energy-time uncertainty relations, particle and anti-particle annihilate one another shortly thereafter without traveling very far. These virtual pairs can be polarized in much the same way as molecules in a dielectric solid. Thus in QED the presence of an electric charge e_0 polarizes the "vacuum," and the charge that is observed at a large distance differs from e_0 and is given by $e = e_0/\epsilon$, with ϵ the dielectric constant of the vacuum. The dielectric constant depends on the distance (or equivalently, in a relativistic setting on energy) and in this way the notion of a "running charge" varying with the distance being probed, or equivalently varying with the energy scale, is introduced. Virtual dielectric screening tends to make the effective charge smaller at large distances. Similarly virtual quarks and leptons tend to screen the color charge they carry.

It turns out however that non-Abelian gauge theories like QCD have the property that virtual gluons "antiscreen" any color charge placed in the vacuum (and in fact overcome the screening due to the quarks). This means that a color charge that is observed to be big at large distances originates in a charge that is weaker at short distances, and in fact vanishingly small as $r \to 0$. This phenomenon has been called asymptotic freedom. The discovery of the antiscreening in spin 1 non Abelian gauge theories was made independently by 't Hooft in 1972, and by David Politzer and by David Gross and Frank Wilczek in 1973: non-Abelian gauge theories behave at short distances approximately as a free (non-interacting)theory. This behavior, called *asymptotic* freedom, could explain in a natural way the SLAC experiments on deep inelastic scattering of electrons by protons. Some physicists speculate that in non-Abelian gauge theories the complement to asymptotic freedom at short distances is confinement at large distances. This would explain the non-observability of free quarks. In other words, even though the forces among quarks become vanishingly small at short distances, the force between them increases very strongly at large distances. Although to this day confinement has not been proved in a rigorous fashion, nonperturbative calculations point to the correctness of the assumption.

The past two decades have seen many successful explanations of high-energy phenomena using QCD. The detection and identification of the $W^\pm$ and of the Z_0 in 1983 by Carlo Rubbia and coworkers at CERN gave further confirmation. Similarly, the empirical data obtained in lepton and photon deep inelastic scattering, and in the study of jets in high energy collisions, can be accounted for quantitatively by QCD. Furthermore, computer simulations have presented convincing evidence that QCD confines quarks and gluons inside hadrons. Frank Wilczek, one of the important contributors to the field, remarked at a conference in 1992 devoted to an assessment of QCD that it had become mature enough to be placed in its "conceptual universe with appropriate perspective."

SILVAN S. SCHWEBER

ELEMENTS, CHEMICAL. Antoine-Laurent Lavoisier's *Traité élémentaire de chimie* (1789) introduced the modern definition of elements. Lavoisier explicitly rejected the obsolete four-element theory of matter, dating to Empedocles and Aristotle, in which everything was believed to be composed of earth, air, fire, and water, combined in varying proportions. The supposed four elements conveyed different pairs of essential qualities: earth the cold and dry; water, cold and wet; fire, hot and dry; air, hot and wet. One prediction from the four-element theory that Lavoisier specifically refuted was the transmutability of water into earth.

Lavoisier proposed that the term "elements," or principles of bodies, should refer only to the endpoint of observational analysis—those substances into which bodies have been reduced by decomposition. This made experiment the final arbiter and so improved on Robert Boyle's earlier more metaphysical definition of elements as perfectly unmixed bodies. Lavoisier drew up a list of thirty-three elements, or simple substances, including metallic and nonmetallic solids; earthy substances; the gases oxygen, nitrogen (azote), and hydrogen; and light and heat (caloric). Louis Bernard Guyton de Morveau, Antoine François de Fourcroy, and Claude Louis Berthollet were among Lavoisier's collaborators who also contributed to what became known as an eighteenth-century revolution in chemistry.

The new chemistry regarded an element as a simple substance with observable properties; compound substances were made up of one, two, or more simple substances. In his *New System of Chemical Philosophy* (1808–1810), the natural philosopher John Dalton identified each of the simple substances or elements with indivisible atomic particles and characteristic combining weights. Dalton devised combinatorial rules and visual images to describe the composition of ordinary bodies by fixed numbers of atom elements, taking hydrogen to be the smallest and lightest element, with an arbitrary atomic weight of 1 unit.

Between 1790 and 1844, thirty-one new elements were discovered, although in some cases without separation from their oxides. Chemists identified these elements and their properties by traditional analytical techniques, supplemented in the early nineteenth century by electrochemical decomposition and replacement by potassium. No further elements were identified until 1860, when Robert Bunsen and Gustav Kirchhoff noted unusual blue spectral lines in the spectrum of a salt. They gave the name "cesium" (from Latin *caesius,* "blue of the firmament") to the supposed emitter. The following year they discovered rubidium from its dark red spectral lines in certain alkaline compounds. The spectroscope figured in the discovery of thallium by William Crookes in 1861, and of indium in 1863, gallium, the rare earths, and the noble gases.

With the proliferation of elements beyond Lavoisier's table of thirty-three, many natural philosophers and chemists speculated that there must be an underlying basic material in all simple substances. In 1815, William Prout proposed hydrogen as the basic building block, citing the experimental result that gas densities appeared to be exact multiples of the density of hydrogen. Tests of Prout's hypothesis continued over the next decades, even as chemists disagreed whether to take hydrogen or oxygen as the most effective standard for calculating relative combining weights of chemical elements, or atoms. By 1860, chemists were convinced that the careful measurements of Jean-Servais Stas demonstrated that atomic weights could not be multiples of 1 or 0.5 or 0.25 as a fundamental protyle.

In 1860, approximately 140 chemists convened at an international chemistry congress in Karlsruhe to discuss standardization of conventions for atomic weights and molecular formulas. Charles Frédéric Gerhardt's system, in which water has the composition H_2O ($H = 1$, $C = 12$, and $O = 16$), was widely adopted. During the era, scientists including Johann Wolfgang Döbereiner, Alexandre-Émile Béguyer de Chancourtois, and John Newlands attempted systematic groupings of the elements. During the 1860s, Dmitrii Mendeleev, professor of technical chemistry in St. Petersburg, used Gerhardt's formula convention, along with combining values, or valences, and the analysis of other properties to develop what he called a natural system of the elements. By early 1869, Mendeleev arrived at a law relating atomic weights to periodicity of properties. His periodic table left blank spaces for unknown elements. The idea of natural families also informed the table of elements published in 1864 by Lothar Meyer. In 1870, Meyer first used increasing atomic weights as the basis of vertical arrangement, complemented by horizontal arrangement of families, and a separate graphical figure plotting atomic weights against atomic volumes. Meyer's short paper of March 1870 brought wide attention to Mendeleev's publication of the previous year.

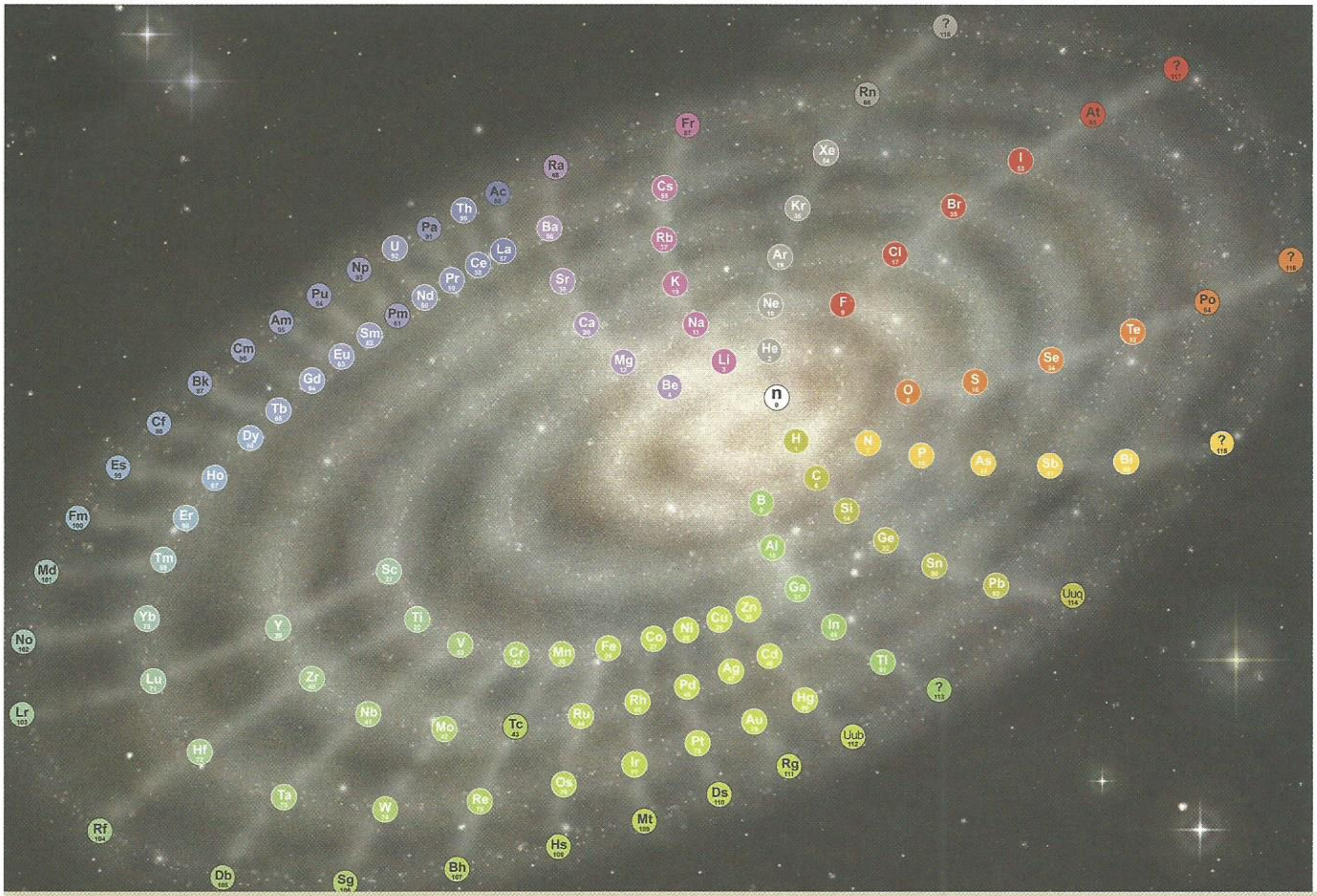
In 1875, Paul Émile Lecoq de Boisbaudran discovered the element gallium, which fit neatly into Mendeleev's blank space below aluminum, an important confirmation of his law of periodicity. Other predicted elements followed in 1879 (scandium) and 1886 (germanium). The known rare earths doubled in number from 1869 to 1886 and proved difficult to classify. In 1913, Henry G. J. Moseley demonstrated the existence of a constant relationship between the frequency of the shortest x-ray line emitted by an element and what Moseley, following A. Van den Broek, termed atomic number, beginning with 1 for hydrogen. Moseley correctly predicted that there must be ninety-two natural elements up to and including uranium. Atomic number replaced atomic weight as the organizing principle for the periodic table of the elements.

Radioactivity produced elements possessing the same atomic numbers and chemical properties as well-known chemical elements, but with different atomic weights. Frederick Soddy coined the term "isotope" to signify any of these chemically identical "elements." In 1912, Joseph John Thomson obtained results suggesting that the inert gas neon (atomic number 10) is a mixture of neon atoms weighing 20 and 22. After World War I, Francis Aston designed a mass spectrograph that sorted out ions by weight and determined that isotopes can be found generally among the chemical elements. Thus a chemical element had a unique atomic number, but an average atomic weight determined by the relative abundance of its isotopes.

Following James Chadwick's discovery of the neutron in 1932, physicists and chemists systematically irradiated elements of the periodic table. Enrico Fermi and his collaborators found that neutrons that had been slowed down were more effective than fast neutrons in producing radioactive isotopes. Fermi's group believed that it had created elements heavier than uranium (atomic weight 238 and atomic number 92) when, in 1934, their irradiations of uranium produced new activities. Similar work by Irène Joliot-Curie and Frédéric Joliot and by Lise Meitner, Otto Hahn, and Fritz Strassmann, resulted in the discovery of uranium fission.

In 1940, Edwin M. McMillan and Philip H. Abelson produced the transuranium element 93 (neptunium) by bombarding uranium with neutrons in a Berkeley cyclotron. Glenn T. Seaborg and his colleagues produced element 94 (plutonium) in the same way in 1941.

At the end of the twentieth century, scientists recognized 112 elements. Of these, 90 occur in nature either free or in combination with other elements; three (atomic numbers 110–112) had not been named formally by the end of 2000. Since the introduction of Mendeleev's and Meyer's tables of 1869 and 1870, the form for the classification of the elements by means of a periodic system has changed remarkably little. The current asymmetrical rectangular table, in which the lathanide series (numbers 57–70) and the actinide series (numbers 89–102) fall outside the main body of the table was largely the design of Seaborg. A pyramidal periodic table, a form originally favored by Niels Bohr, has been proposed but has not come into general use despite its more symmetrical appearance. The elements are today recognized not as simple substances in the physical meaning of undecomposable primary matter, but as basic substances in



Periodic table represented as a galaxy, the lighter elements nearer the center. The halogens are in red, transition metals in green, lanthanides and actinides in blue.

the chemical sense of fundamental matter that exists freely or virtually in all known bodies.

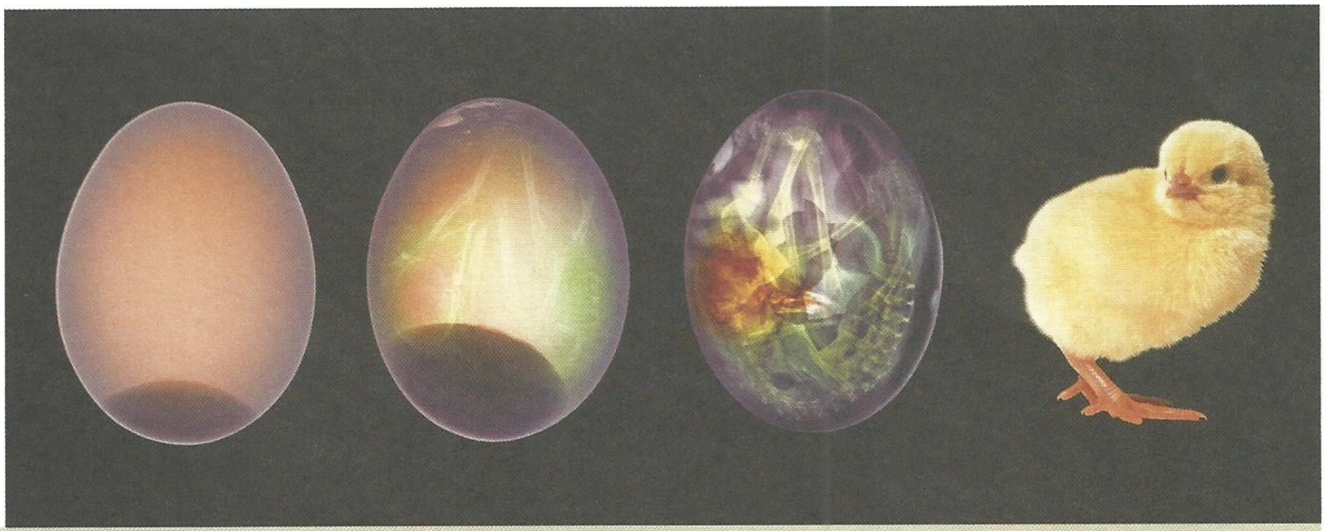
Mary Jo Nye

EMBRYOLOGY. The embryo and its development have been investigated since antiquity and, with few exceptions until the early nineteenth century, under the heading "generation." During the mid-1900s, the term "embryology" denoted the branch of anatomy or physiology concerned with the development of the individual before birth. At the end of the nineteenth century the perception of embryology as a distinct discipline encouraged some universities to establish chairs in "embryology and histology." Given the sensitive character of their subject matter, embryological investigations often reflected deep religious, philosophical, and gender beliefs and influenced legal and social issues.

By breaking open day after day eggs hatched by a hen, Aristotle recorded a sequence of observations on the development of the chick. On the third day he observed a palpitating heart and later distinguished a head with prominent eyes clearly separate from the rest of the body. Aristotle held that the first organ to develop in the embryo was the heart, which he considered to be the control core of animal life and the source of vital heat. He also maintained that death occurred when the heart stopped beating. During the Renaissance Aristotle's observations on the developing chick, a subsidiary part of his theory of generation, were replicated and examined by Ulisse Aldrovandi, Volcher Coiter, and Girolamo Fabrici, who investigated many viviparous animals using a comparative approach (*Deformatione ovi et pulli,* 1621).

Drawing an analogy with shipbuilding, Fabrici believed that the embryo would build itself up from a bony framework, a view harshly criticized by his pupil William Harvey in his *De generation animalium* (1651). Harvey based his theories on numerous observations and dissections of domestic fowl and deer carried out over many years. Although he never saw the ova of vivipera, he postulated that all female animals produced them and that their development followed the pattern of ovipera. Because his dissections of the uteri of fowl and deer after mating never revealed conception in the form of a mixture of male and female semen, he rejected ancient doctrines of conception. Instead, he held that females produced eggs endowed with a vitality that, with no material contribution, could be stimulated to develop by the male's semen. By focusing on a little scar (Fabrici's *cicatricula,* i.e., the blastoderm) on the surface of the hen's fertilized egg, Harvey made his most important discovery, namely that after the first day it started germinating. He also described how the chick developed from the *cicatricula* by budding and subdivision in sequence. He named this process "epigenesis." Contrary to Aristotle, Harvey maintained that the blood and not the heart formed first.

During the second half of the seventeenth and the eighteenth centuries, many scholars opposed Harvey's epigenesis with the alternative theory that development consisted in the unfolding and growth of all the parts of the adult organism, which pre-existed miniaturized in the egg. In his *Dissertatio epistolica de formatione pulli in ovo* (1673), Marcello Malpighi compared the development of the chick to that of plants, considered the intake of food from the yolk and albumen, and described how the parts of the embryo change shape and position before acquiring resemblance to their adult form. His description of embryogenesis and his discoveries (e.g., of



Colored X-ray photographs of the development of a chicken. Left to right: at six days, twelve days, eighteen days, and 21 days

the cardiac tube, the neural folds, and the neural tube) had a profound impact upon embryological research.

During the eighteenth century the opposition between these two main views of embryogenesis culminated in the controversy between Albrecht von Haller's mechanistic preformationism and Caspar Friedrich Wolff's vitalistic epigenesis. Wolff maintained that, just as plants formed from the structureless substance of the vegetational bud, so the chick emerged from a homogeneous primordium through the secretion and solidification of fluids regulated by a *vis essentialis* (essential force) present in living matter (*Theorie von der Generation,* 1764). Despite Wolff's denial that organs pre-existed in a latent form and his insistence that preformation was a chimera, epigenesis acquired preeminence only during the nineteenth century.

The period 1820 to 1880, the age of classical descriptive embryology, saw the seminal works of Christian Heinrich Pander, Karl Ernst von Baer, Martin Heinrich Rathke, Rudolf Albert von Koelliker, Robert Remak, Ernst Haeckel, Oscar Hertwig, Richard Hertwig, Francis Maitland Balfour, Aleksandr Kovalevsky, and others. Improvements of the microscope first, and then the combined introduction of the microtome and staining techniques, helped overcome some of the technical barriers that had frustrated previous investigators in their observations. Study of the embryo was much influenced by morphology in the 1820s and 1830s, by cell theory in the 1840s and 1850s, and by the theory of evolution from the 1860s onwards. It was also influenced by the ideal, typical of the century, of furnishing historical explanations. Applied to the embryo, this ideal postulated that knowledge of the organization of living entities could be achieved only by investigating their gradual development. It also suggested a parallelism between the stages of development of the individual organism and the long-term transformations of the entire animal series.

One major contribution of early nineteenth century embryology was the doctrine of germ layers. In 1817, Pander described how the chick's blastoderm (a term he introduced) developed into three separate layers, which he considered to be the antecedents of later structures (*Beiträge zur Entwicklungsgeschichte des Hühnchens im Eye*). In the 1820s, von Baer maintained that the germ-layer concept applied to other vertebrates as well, and Rathke extended it to invertebrates. In papers published between 1850 and 1855, Remak demonstrated that germ layers consisted of cells. Thus the goal of much embryological research of the time became that of tracing the origin of a single organ to a specific germ layer. In 1867–1871 Kovalevsky reported compelling observations that evidenced the universality and specificity of the germ layers. "Mesoderm" was coined in 1871, and "ectoderm" and "endoderm" in 1872, to denote the three germ layers. The doctrine of the absolute specificity of the germ layers has been disputed by more recent embryological research, which has emphasized the interactions among the layers as they develop.

Perhaps the most significant contribution of embryology during the early eighteenth century was the clarification of the fertilization mechanism. In papers published in 1824–1825 Jean-Louis Prevost and Jean-Baptiste-André Dumas described filtering experiments that showed that spermatozoa played an essential role in fertilization, and in 1827 von Baer announced the discovery of the egg, first in dogs and then in other mammals (*De ovi mammalium et hominis genesi*). In 1841, Koelliker argued for the cellular origin of spermatozoa and in 1844 suggested that the ovum is a cell. In the early 1850s Remak proved the cellular nature of the egg and argued that the original fertilized egg with its nuclear content underwent a process of division (cleavage) until it formed the germ layers. At that time, however, the prevailing theory of fertilization still denied that spermatozoa made any material contribution to the embryo. A host of investigations of animals and plants conducted by many scholars between 1875 and 1880 led to the conclusion that fertilization consisted in the union of a part of one spermatozoon or pollen with an egg or ovule. This fusion of two cells produced the unicellular fertilized egg that only then began dividing to form the embryo. This theory aroused great excitement because it explained the continuity of life by establishing a bond between generations through the transfer of some material substance from the parents to the new individual.

Nineteenth-century embryology sought laws of development. Von Baer enumerated four laws, which account for his endorsement of epigenesis and the existence of different types of embryonic development, and therefore the organisations that he had distinguished (radiates, articulates, mollusks, and vertebrates). In post-Darwinian thought the notion of evolutionary change eroded the type concept. A major problem, therefore, was envisaging a law that considered the results obtained by descriptive embryology and simultaneously accounted for individual and ancestral development. A law, later known as the biogenetic law, formulated by Haeckel in 1866 stated that ontogeny (the development of the individual) briefly recapitulates phylogeny (the development of the organic lineage to which it belongs) determined by heredity and adaptation (*Generelle Morphologie der Organismen,* 1866). This law had considerable impact upon nonspecialists as well and acquired dogma-like status. The next generation of embryologists raised doubts about recapitulation and, in order to gain better understanding of the mechanisms of development, turned once again to problems of causation, this time however by experimenting directly on the embryo.

Renato G. Mazzolini

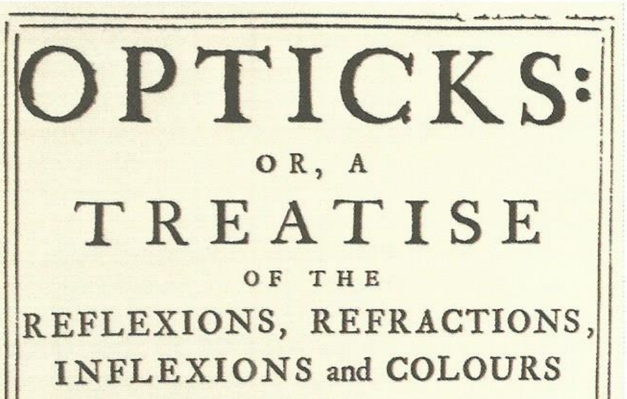
ENCYCLOPEDIAS. We owe the word "encyclopaedia" to Quintilian's Latinized version of the Greek term denoting a circle of study or learning. This concept came to inform the notion of the seven liberal arts that passed into the medieval university curriculum. This set of favored subjects included geometry and some natural knowledge and appears in all major medieval and Renaissance encyclopedias, for example Gregor Reisch's *Margarita Philosophica* (1496) and Johann Heinrich Alsted's *Encyclopaedia* (1 vol., 1620).

During the early eighteenth century, a new encyclopedic genre, the dictionary of arts and sciences, made its appearance. It included information on the arts and crafts that had previously been excluded from liberal sciences and the universities. Antoine Furetière's *Dictionnaire Universel* (3 vols., 1690) and John Harris's *Lexicon Technicum* (2 vols., 1704, 1710) were the first examples. These works differed from the historical dictionaries of the time, such as Louis Moréri's *Grand Dictionnaire Historique* (2 vols., 1674) and Pierre Bayle's *Dictionnaire Historique et Critique* (2 vols., 1697), which covered history, geography, and biography rather than the arts and sciences. Knowledge was becoming specialized. The *Grosses vollständiges Universal Lexicon,* begun in 1732 by the Leipzig publisher Johann Zedler, which has entries on scientific topics as well as on history, theology, philosophy, and biography, reached sixty-four folio volumes by 1750. The much slimmer dictionaries of arts and sciences did not have biographical entries and treated history and geography only insofar as they were relevant to the account of technical terms.

These so-called "scientific dictionaries" focused on natural, mathematical, and craft or technical knowledge. The strength of Harris's *Lexicon* in mixed-mathematical subjects and their application in areas such as navigation, architecture, fortification, gunnery, and shipbuilding earned him the nickname "technical Harris." A member of the Royal Society (serving as its secretary in 1710), Harris incorporated substantial quotations from Isaac Newton's *Opticks* (1704), which had just come out in English translation, and inserted an unpublished paper by Newton on acids in the second volume. Ephraim Chambers's *Cyclopaedia* (2 vols., 1728) built more widely on Harris's foundations. It claimed to contain a well-rounded course of ancient and modern learning, thus justifying its use of "cyclopaedia." Like Harris, Chambers covered subjects still categorized as scientia, such as law, grammar, music, and theology. He gave more attention to crafts and trades that fell outside the area of practical mathematics treated by Harris: paper, soap- and glass-making, mining, forging, weaving, bleaching, dying, tanning, and the manufacture of cloth and pins. But Chambers distinguished between "Mechanical Arts ... wherein the Hand, and Body are more concern'd than the Mind" and the mechanical sciences. In keeping with the implied preference, the *Cyclopaedia* was stronger on the "sciences" than the "arts," although later editions promised to improve the coverage of trades and manufacturing arts.

The content of these dictionaries of arts and sciences gives a clue to their commercial success. They provided information on subjects, such as the mechanical arts, excluded from university education together with detailed entries on the major mathematical and physical sciences: the dictionaries of Harris and Chambers amounted to practical manuals and Newtonian textbooks. Both appeared on study guides at Cambridge, and students were directed to read particular entries. Harris and Chambers treated chemistry, medicine, and natural history less fully, possibly because specialist lexicons for these subjects already existed. They met a need not only in England but also in Europe. Chambers's *Cyclopaedia* appeared in two Italian translations (Venice, 1748–1749, and Naples, 1747–1754), and inspired the creation of the greatest of all the eighteenth-century compendia of knowledge, the *Encyclopedie, ou Dictionnaire raisonné des arts et sciences* of Denis Diderot and Jean Le Rond d'Alembert (17 vols. of text and 11 vols. of plates, 1751–1772).

Eighteenth-century encyclopedias were published and sold by subscription. This method, introduced by English booksellers early in the seventeenth century, tested the market for large and expensive works. A prospectus announcing the work gave the names of subscribers and helped recruit additional ones. The range of occupations represented in these lists—from bishops and physicians to watchmakers



OPTICKS:
OR, A
TREATISE
OF THE
REFLEXIONS, REFRACTIONS,
INFLEXIONS and COLOURS
OF
LIGHT.
ALSO
Two TREATISES
OF THE
SPECIES and MAGNITUDE
OF
Curvilinear Figures.

LONDON,
Printed for Sam. Smith, and Benj. Walford,
Printers to the Royal Society, at the *Prince's Arms* in
St. *Paul's* Church-yard. MDCCIV.

Title page from Newton's *Opticks*

and printers—indicate the breadth of the market. The first volume of Harris's *Lexicon* cost twenty-five shillings, and Chambers's two folios cost four guineas, both expensive compared with the price of monthly magazines, about six pence an issue in 1750. Subscription and serialization placed the early English scientific dictionaries within the reach of a wider group of readers than the first edition of the *Encyclopédie,* which initially cost 280 livres (around 11 guineas) and rose to 980 livres (40 guineas) by the 1770s.

Three significant changes in encyclopedias may be discerned over the course of the eighteenth century. First, the scope and importance of the nonscientific content increased: although the *Encyclopédie* did not admit biographical entries, it boasted large and sometimes controversial essays on topics in history, literature, music, art, politics, and philosophy. Perhaps its most distinguished feature, apart from its anticlericalism, was its comprehensive documentation of the arts, crafts, and trades, which it illustrated with some 2,500 engravings. In this aspect of their work, the encyclopedists claimed inspiration from the philosophy of Francis Bacon.

Second, the format shifted from relatively compressed entries on terms (the style of both Harris and Chambers) to longer essays, still arranged alphabetically. The *Encyclopaedia Britannica,* issued in one hundred installments from 1768 and published in Edinburgh in three volumes in 1771, departed from the format of the earlier dictionaries of arts and sciences, presenting the sciences as "systems" in separate treatises of at least twenty-five pages each. The *Encyclopédie Méthodique* (66 vols., 1782–1832)—the successor to the *Encyclopédie*—amounts to a set of specialist treatises, in which, in the words of a contemporary reviewer, "every science will have its dictionary, or system, apart."

The third development was the recruitment of specialists to write the articles. The *Encyclopédie* engaged some of the most distinguished natural philosophers and academicians of France, especially Gabriel François Venel in chemistry, Louis-Jean-Marie Daubenton in anatomy and zoology, Nicolas Desmarest in geology, and, of course, d'Alembert in mathematics. The third edition of the *Britannica* (10 vols., 1788–1797) followed suit. Whereas William Smellie (the main compiler of its first edition) wrote many of its treatises by collating from various books, the third edition brought in experts. For its six-volume *Supplement,* its editor, Macvey Napier, commissioned leading men of science to update articles, such as those in natural philosophy formerly done by the Edinburgh professor John Robison.

British competitors of the *Britannica* such as Abraham Rees's *New Cyclopaedia* (45 vols., 1802–1819), David Brewster's *Edinburgh Encyclopaedia* (18 vols., 1809–1830), and the *Encyclopaedia Metropolitana* (28 vols., 1829–1845) all gave science high priority and sought out leading contributors. The *Metropolitana* boasted contributions from Charles Babbage and John Herschel, who wrote extensive treatises on astronomy, light, and sound. The ninth edition of the *Britannica* (1875–1889) responded with "Physical Sciences" by James Clerk Maxwell and "Evolution in Biology" by Thomas Henry Huxley.

All but one of these nineteenth-century works abandoned the maps of knowledge that delineated the relationships between the branches of science. The exception, the *Metropolitana,* was arranged not alphabetically, but rather on a classification published in 1817 by Samuel Taylor Coleridge that placed subjects in logical or systematic order. All branches of mathematics preceded Herschel's articles on light and sound because these subjects assumed prior mathematical knowledge. The *Metropolitana* did follow the nineteenth-century practice of assigning detailed articles on scientific disciplines to experts, which raised concerns about the role of encyclopedias as a medium for the public communication of knowledge. The *Britannica* eventually found a solution. Its great eleventh edition of 1911 marked the high tide of the expert article. It then floated from Cambridge University Press to the United States, at first to Sears, Roebuck and Company and later to the University of Chicago Press. From the 1930s it was sold by door-to-door salesmen as an indispensable aid to social success. The revised fifteenth edition (from 1974) of the *Encyclopaedia Britannica,* which is now published by an independent corporation, came in two versions: a "micropaedia" for quick reference and a "macropaedia" for detailed specialist articles. This division resolved the tension between the interests of most people and the scholarly imperative.

During the nineteenth and twentieth centuries, European countries and the Soviet Union created encyclopedias emphasizing their national cultures within the international circle of knowledge. The most important of these works for the history of science is the *Enciclopedia Italiana* with its collateral publications. They are the products of the Istituto della Enciclopedia Italiana, founded in 1927 by the industrialist Giovanni Treccani and directed in its scientific program by the philosopher Giovanni Gentile. The *Enciclopedia* itself, complete in thirty-six massive volumes (1929–1939), is among the world's best. When supplemented by the Istituto's *Dizionario biografico degli Italiani* (now to the letter "G" in 55 volumes, 1960 to the present) and its specialized series in art, architecture, and so on, it represents the grandest attainment of the encyclopedia as a cultural resource. The Istituto is currently publishing a *Storia della scienza,* which will extend encyclopedism with an encyclopedia of the history of science twenty times the size of this Companion.

RICHARD YEO

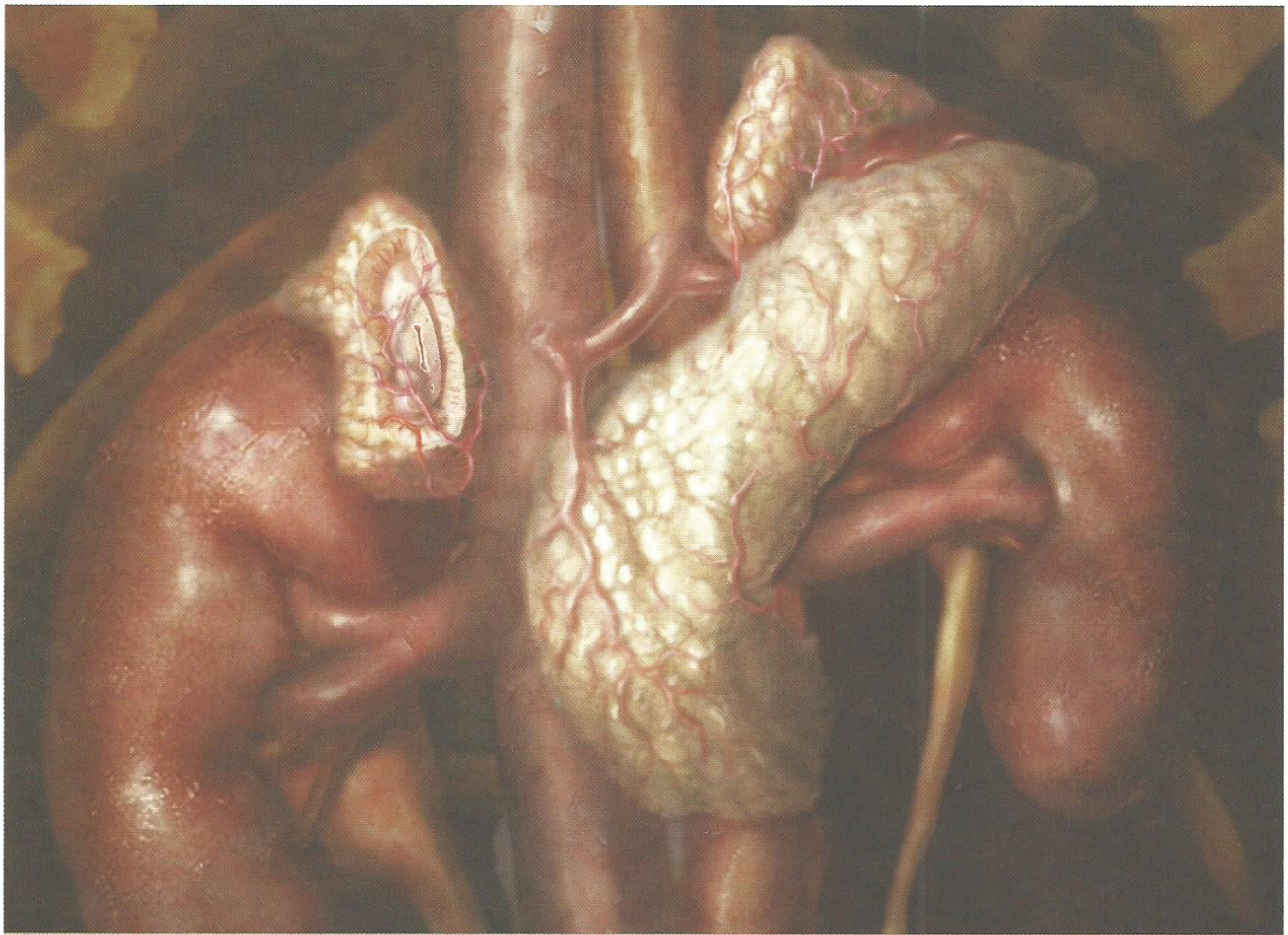
ENDOCRINOLOGY. The clinical specialty of endocrinology is less than a century old, but knowledge of endocrine diseases and the structures and functions of the endocrine glands has a much longer history. The physicians of antiquity described the effects of castration and diseases such as diabetes and treated simple enlargement of the thyroid (goiter) with burnt sponge or seaweed, now known to contain iodine. The anatomy of the testes, ovaries, thyroid, pituitary gland, and adrenals was long known, although as separate structures, rather than a loosely connected endocrine system. In the eighteenth century, Albrecht von Haller noted the existence of "glands without ducts," which he distinguished from ducted ones such as the salivary and sweat glands. A century later Claude Bernard crystallized the notion of "internal secretion" when he distinguished between the "external" secretion of bile by the liver and its internal one of sugar.

Despite these and many other anatomical, physiological, and pathological insights, endocrinology as a coherent body of knowledge did not emerge until the early twentieth century. It then carried with it the newsworthy but ambiguous legacy of Charles-Edouard Brown-Séquard, a serious scientific clinician who introduced in the 1880s testicular extracts as a sensational agent of rejuvenation. Brown-Séquard's death soon after his self-experimentation deflated the notion of frolicking octogenarians, but a second potent endocrine extract, from the thyroid gland, had demonstrable physiological effects. By the 1890s, the cluster of clinical conditions variously described as cretinism, myxoedema, and cachexia strumipriva had been referred to a failure of the thyroid gland. In 1891, George Murray reported the successful treatment of myxoedema with thyroid extract. That the mixture also acted as a stimulant gave it wider appeal, and it was frequently prescribed for lethargy, obesity, and general malaise.

The hormone concept appeared in 1902, when the British physiologists William Bayliss and Ernest Starling identified in the mucosa of the duodenum a substance they called "secretin." It could stimulate secretion by the pancreas even when the neurological connections were severed. This action pointed towards a chemical stimulus; three years later Starling called this class of substances "hormones," from the Greek for "to excite." The subsequent coining of the word "endocrine," from Greek words for "within" and "separate," codified the notion that hormones flow directly into the bloodstream and act on other organs or cells without the intermediating functions of the nervous system. Edward Sharpey-Schafer's monograph *The Endocrine Organs* (1916) helped define the field. He had earlier (with George Oliver) isolated a blood-pressure raising hormone of the adrenals, adrenaline. Although it took some time for the clinical specialty to rid itself of the enthusiastic claims of an earlier generation, Sharpey-Schafer's scientific synthesis firmly established its experimental roots.

The dramatic therapeutic potentials of the discipline were realized in 1921 when Frederick Grant Banting and Charles Herbert Best isolated insulin, one of the active endocrine products of the pancreas. The Nobel Prize two years later went to Banting and J. J. R. Macleod, in whose lab the work took place, but Banting shared his prize with Best and Macleod his with James Bertram Collip, the biochemist who had assisted in its purification. The relative contributions of the four men have been much debated, but insulin itself stood out as a major therapeutic breakthrough in the treatment of diabetes. The interwar period proved to be a fertile time for endocrinology, with new biochemical and bioassay techniques to identify and purify many active hormones from the ovaries, testes, adrenals, pituitary, thyroid, and parathyroids. In 1936, Edward Doisy (who shared the 1943 Nobel Prize for his work on Vitamin K) defined four criteria by which hormones could be identified. These were: 1: a gland must be identified as producing an internal secretion; 2: the substance must be detectable; 3: it must be capable of being purified; and 4: the pure substance needs to be isolated, purified, and studied chemically. This followed his research on the role of ovarian hormones on the estrus cycle, which in turn laid the foundation for the development of hormonal contraceptives as well as agents to treat menstrual and other gynecological disorders.

Research on the several endocrine glands clarified that hormones belong to various classes of bioactive substances. These include steroids (the gonads and adrenal cortex), catecholamines (adrenal medulla), iodinated amino acids (thyroid), and proteins and active peptides (anterior and posterior pituitary, pancreas, gut, parathyroids, and thyroid). Work on the pituitary by Pierre Marie, Harvey Cushing, and many others proved to be especially significant. Not only does the pituitary synthesize many of the central hormones that regulate peripheral production (through a subtle



Three-dimensional visualization of endocrine glands reconstructed from scanned human data system of negative feedback), it is in intimate contact with the hypothalamus, an area of the brain that also has important controlling functions on the nervous system, especially the autonomic system. The earlier notion that the endocrine system stands functionally apart from the nervous system has thus been fundamentally modified.

Research during the past half-century has been aimed primarily at clarifying the chemical structures, synthetic pathways, and molecular modes of actions of the diverse group of substances called hormones. Since these are involved in many fundamental physiological processes such as metabolism, digestion, growth, reproduction, salt-and-water maintenance, and the interaction of the organism with its environment, endocrinology has maintained its close ties with basic science, especially molecular biology. The complexity of the system allows many ways for it to go awry; the clinical discipline is now sub-specialized, with diabetes, gynecological endocrinology, and the thyroid each having its own group of specialists. Endocrinological surgery is now a recognized specialty, especially important in the treatment of tumors of the endocrine organs.

W. F. BYNUM

ENERGETICS. The great unsettled question of late-nineteenth-century physics was the status of the mechanical worldview. For more than two hundred years—from René Descartes, Christiaan Huygens, and Isaac Newton in the seventeenth century to Hermann von Helmholtz, Heinrich Hertz, and Ludwig Boltzmann at the end of the nineteenth—physicists had generally sought mechanical explanations for natural phenomena. As the nineteenth century drew to a close, Hertz reaffirmed the classical goal of physical theory: "All physicists agree," he wrote in the preface to his *Principles of Mechanics* (1894), "that the problem of physics consists in tracing the phenomena of nature back to the simple laws of mechanics." But when these words were published, physicists were no longer in general agreement about the nature of their project. Many doubted, and some explicitly denied, that mechanics was the most basic science. Other candidates contended for the honor—thermodynamics and electromagnetic theory, in particular, and several comprehensive alternatives to the mechanical worldview were proposed and vigorously debated throughout the 1890s and early 1900s.

Energetics was one of the alternatives. Tracing its origins to the founders of the law of energy conservation, especially Robert Mayer, and to the thermodynamic writings of Rudolf Clausius, William Thomson (Lord Kelvin), and Josiah Willard Gibbs, energetics attempted to unify all of natural science through the concept of energy and by laws describing energy in its various forms. The energeticists believed that scientists should abandon their efforts to understand the natural world in mechanical terms and should give up atomism as well in favor of a new worldview based entirely on relations among quantities of energy.

Energetics as a scientific project of the late 1880s and 1890s took place largely in Germany. (A prominent exception was the work of the French physicist Pierre Duhem.) Its main German proponents were Georg Helm, a Dresden mathematician and physicist, and Wilhelm Ostwald, the professor of physical chemistry at Leipzig. Helm first urged the formulation of a "general energetics" in his *Theory of Energy* (1887), which proposed an "energy principle" (a law more general than the law of energy conservation) as its basis. An essay in 1890 sought to reduce mechanics to energetics by means of this energy principle, and another in 1892 was intended to do the same for electricity and magnetism. In 1894, Helm wrote a book on the energetic development of physical chemistry. These publications elicited an invitation to address the German Association of Scientists and Physicians at their meeting in Lübeck in 1895 on "the current state of energetics."

Ostwald's interest in energy stemmed from his reading, in mid-1886, of Dutch chemist Jacobus van't Hoff's studies in chemical dynamics and from his own efforts, in the late 1880s, to understand the thermodynamic writings of Gibbs, which Ostwald published in German translation in 1892. He was soon converted to the way of "pure energetics," the theory of which he developed in two essays published in 1891 and 1892. He then refined his theory and applied it to a variety of problems in general and physical chemistry in 1893–1894. Always the enthusiast, Ostwald traveled to the 1895 meeting in Lübeck, where he was also on the program, to demonstrate the demise of the mechanical worldview and to promote energetics as its proper replacement.

The heated debate at Lübeck turned out to be a disaster for energetics. The negative reactions of Boltzmann and Max Planck to the energeticists were taken as definitive by younger physicists such as Arnold Sommerfeld and Albert Einstein. Helm and Ostwald later replied to these criticisms, only to be rebutted again by Boltzmann (1896–1898). Ostwald published his *History of Electrochemistry* in 1896; Ernst Mach likely hurried his (incomplete) *Theory of Heat* into print in the same year to support the anti-mechanist cause; and Helm, in his history of energetics of 1898, tried to defend his own work. But the damage had been done. Ostwald continued to uphold energetics after 1900, but increasingly as a monistic worldview, not as a scientific project.

The scientific proposals of the energeticists were flawed, but the attention they received undermines the common assertion that the physical scientists of the late nineteenth century were satisfied with the state of their science. The long tradition of mechanical explanation in the natural sciences was coming to an end. The debate over energetics as a viable replacement for the mechanical worldview reflected the difficulties inherent in the mechanical view.

ROBERT J. DELTETE

ENGINEERING SCIENCE. Although the term "engineering science" first came into widespread use in the early twentieth century, "the science of the engineer" and equivalent phrases had been employed much earlier to signify parts of professional engineering transcending untutored practice, parts of science that could usefully inform innovative practice, and canonical theoretical knowledge qualified to enhance the engineer's professional status. From the mid-nineteenth century, individual engineering sciences became integrated into a systematic field of study, modeled on the physical sciences, but with a content specific to some particular engineering practice.

Recently, commentators seeking to develop an independent field of the history of technology have redefined engineering science as a "mode of knowledge" distinct, in content and style, from any physical science (David Channell, *The History of Engineering Science* [1989]). John M. Staudenmaier, S. J., writes of "engineering theory" as a "body of knowledge using experimental methods to construct a formal and mathematically structured intellectual system" *(Technology's Storytellers: Reweaving the Human Fabric* [1985]) to explain the behavior of a particular class of (idealized) artifact or of artifact-related materials. Its experimental methods involve models, testing machines, towing tanks, and wind tunnels; it is structured by the demands of practice, and thus develops ways of comparing models with full-scale apparatus, often relying on pragmatic approximation rather than rigor.

According to this model, engineering science has provided a common language through which a community of status-conscious practitioners has articulated its increasingly specialized concerns. Furthermore, a network of professional societies, schools, and laboratories, and a technical literature, existing especially in Europe and the United States from the late nineteenth century, catered to the creation, inculcation, and critical evaluation of engineering science. Those institutions acted as a cohesive and mediating force, orchestrating a transition from the scattered skills and knowledge associated with local problem-solving to the standardized, universal, and abstract theories, designs, and practices issuing from the schools.

Historical investigation reveals variations and tensions within this schematic account. From the late seventeenth century, the Royal Society of London and the Academy of Sciences in Paris gave a central role to natural philosophy in perfecting practical arts for the public good. In the aftermath of the French Revolution, plans for a reformed and centralized system of engineering training, designed to foster economic health, were implemented. The École Polytechnique (1794–1795) in Paris exemplified the militaristic production of technocrats. Elite savants furnished bright student engineers with a core curriculum concentrating on mathematics and theoretical sciences in readiness for the traditional branches of engineering (bridges, roads, artillery, mining) taught at the *écoles d'application.* While the École Polytechnique tended to eschew practical concerns, the École Centrale celebrated its distinctive *science industrielle* as a means of producing neither savants nor artisans but men who were at once scientists, generalists, and technological problem-solvers for the new industries.

The École Polytechnique's first director, Gaspard Monge, did, however, create a science of descriptive geometry (1795) for engineering drawing; founder Gaspard de Prony published the influential *Architecture hydraulique* (1790–1796); Lazare Carnot generalized the study of machine efficiency. Subsequent engineering theorists, many of them alumni of the school, included Charles Burdin (turbines); J. V. Poncelet (author of the *Mécanique industrielle* [1829]); J. N. P. Hachette *(Traité élémentaire des machines* [1811]); and C. L. M. H. Navier (who revised Belidor's *Architecture hydraulique* [1819]). They replaced the abstraction and microscopic model-building of the physics of Pierre-Simon Laplace with a focus on macroscopic phenomena and (especially in the case of Jean Poncelet and Gaspard Coriolis) transformed engineering mechanics from an offshoot of rational mechanics into a new science of work.

If the stereotypical European engineer was scientifically schooled but industrially ineffectual, his British equivalent

The Iron Bridge spanning the River Severn at Coalbrookedale in Shropshire, England (1779). The first cast-iron bridge in the world, it has become a symbol of the Industrial Revolution.

was economically potent and scientifically illiterate. Practical apprenticeship, according to received wisdom, made the British engineer. Yet he too had at his fingertips a miscellany of "modern improvements" in handbooks, encyclopedias (such as those of Abraham Rees and, later, Andrew Ure), parliamentary reports, works of mathematical practice by men such as Charles Hutton and Olinthus Gregory (associated with the military colleges), and Thomas Tredgold's classics on carpentry (1820) and cast iron (1822). This scattered literature sat beside scientific transactions in the libraries of new engineering associations which, like the Institution of Civil Engineers (1818) in London, produced their own publications.

In Britain, the consolidation of the science of the engineer coincided with the establishment of the university-based engineering education, with one eye on European models (especially the Freiberg School of Mines) and the other on an agenda of professionalization. From the 1820s, the Mechanics Institutes (such as the Franklin Institute in the United States) targeted artisans with popular science. From the late 1830s, educators at King's College and University College in London offered mathematics, chemistry, geology, and natural philosophy to student engineers, and the Edinburgh natural philosopher James David Forbes examined "academical engineers" at the new Durham University. Low-status lecturers or demonstrators gave practical tuition (for example, in surveying), but the scientific engineer had still to complete his training with a practical apprenticeship.

From the 1840s, professors of engineering in Britain and the United States gradually articulated a corpus of unified engineering theory. Their strategies varied. Lewis Gordon in Glasgow assembled the best of collective contemporary engineering experience in a textbook keenly attuned to recent European developments (especially Benoit Fourneyron on turbines, and Gordon's mentor at Freiberg, Julius Weisbach, for hydraulics, the mechanics of machinery, and "mechanical effect"). Charles Blacker Vignoles codified railway construction in lectures reproduced in London-based newspapers. Eaton Hodgkinson collaborated with industrialist William Fairbairn and the British Association for the Advancement of Science (founded in 1831) in developing experimental regimes for the study of new engineering materials (wrought and cast iron) and innovative structures (notably the Britannia Bridge).

At the other extreme, Robert Willis's *Principles of Mechanism* (1841) mimicked the forms of deductive geometry in its kinematics, or the classification of modes of communicating motion by machinery independent of force. A standard university text, its techniques were superseded only by the work of Franz Reuleaux at the end of the century. Henry Moseley's *Mechanical Principles of Engineering and Architecture* (1843) and especially William Whewell's *Mechanics of Engineering* (1841) borrowed from French theorists of structures and work while aiming, like Willis, to place sanitized and "progressive" engineering sciences within an English liberal education.

In systematizing engineering knowledge, these author-professors acted as mediators between disembodied recent science and actual (or potential and lucrative) industrial concerns; as translators, directing the application of science to practice; or as organizers of disorganized craft practices. Such roles are consistent with Eugene Ferguson's claim that the province of the engineering sciences lay between "pure physical science" and the "empirical and intuitive knowledge of the engineer" (*Bibliography of the History of Technology* [1968]). Despite Auguste Comte's insistence that the engineer, although responsible for organizing the mediation between science and practice, was not a man of science, the École Centrale claimed that "industrial science" readied its students to mediate between a complex body of scientific knowledge and its applications to industry, and the *Engineer* insisted (1856) that the application of science to practice was itself a science.

W. J. M. Rankine's practically oriented work in thermodynamics and good relations with local industrialists secured him a chair of engineering in Glasgow (1855). From there he argued that the academically trained engineer bridged the gap between distinct worlds of natural philosophical questions (what are we to think?) and practical questions (what are we to do?). The scientific engineer worked without waste, husbanding human and natural resources, economically achieving the practical aims precisely delimited by exact theoretical science, bearing in mind the quantifiable constraints of the market. With Rankine's Certificate of Proficiency in Engineering Science (from 1862), an engineer could plan with certainty and innovate with confidence.

A forum for topical scientific engineering discourse existed in technical periodicals, including *Engineering* (1866) and the publications of the Institution of Naval Architects, the American Society of Mechanical Engineers, and many other specialist professional engineering associations. Rankine's monumental and long-lasting textbooks, especially *Applied Mechanics* (1858), defined the bedrock of the scientific engineer. The basic repertoire offered theoretical engineering sciences, including soil mechanics, hydraulics, structures and frameworks, and elasticity, but many found Rankine's works inscrutable and, ironically, divorced from practice.

Thus, Isambard Kingdom Brunel objected to the anti-progressive standardization of engineering science and the "best practices" deduced by government commissions set up to learn from railway disasters, collapsing bridges, or naval catastrophes. These commissions harbored many professorial engineering experts and academicians, such as the electrical engineer Fleeming Jenkin (Edinburgh) and the heat-engine theorist Osborne Reynolds (Manchester), who lobbied for the training of scientific engineers to ensure public safety and economic prosperity. They looked covetously to well-funded institutions, academies, and polytechnics in Europe and the United States, but generally choked at the idea of mass-produced engineers, preferring to nurture a scientifically trained, gentlemanly elite of professional leaders.

In addition to having a theoretical base, the engineering sciences developed distinctive experimental practices. For science-intensive electrical engineering companies (such as Siemens), laboratories produced reliable electrical measures in a context of international standardization. For German *Technische Hochschulen,* the research laboratory linked college technical practice with industrial production. From 1868, the Polytechnic Institute of Munich had a materials-testing laboratory. Toward the end of the nineteenth century, Robert Thurston at Cornell, Alexander Kennedy in London, James Alfred Ewing in Cambridge, and college engineering professors generally argued that purpose-built laboratories, long essentials for chemistry and physics, were now vital to engineering teaching and research, particularly as venues for precision measurement. Trinity College, Oxford, had an engineering laboratory from 1886, and the University followed suit in 1914 with its own lab—well away, however, from the "Science Area."

The engineering science laboratory also modeled practice. Schools of engineering accumulated both demonstration apparatus and experimental models. Exactly what the behavior of a small-scale experimental model or theoretical simulation revealed about its full-sized counterpart was crucial—and unclear. Benjamin Isherwood insisted that only from full-scale experimental researches like his, in steam engineering for the U.S. Navy in the 1860s, could valid general "engineering laws" emerge; the British Association accumulated vast quantities of (unreducible) data relating engine power, ship shapes, and speeds on a similar understanding (voiced by naval architect C. W. Merrifield). Economic pressures forced engineers to learn how to "scale up." In hydrodynamics, John Scott Russell's "wave-lines" and Rankine's "streamlines" pointed plausibly to low-resistance hull shapes; but from the late 1860s, William Froude turned, additionally, to experimental tanks. In aeronautical engineering, a growth area especially after World War I, wind tunnels could give workable design solutions where fluid dynamics failed. Eventually, computer simulation would complement, and in some respects supersede, those modeling techniques.

At the beginning of the twentieth century, engineering science began to appear as a named academic discipline. Charles Frewen Jenkin, son of the Edinburgh academician and himself an expert in aeronautical materials, entitled his professorial address at Oxford "Engineering Science" (1908). The following decades saw a flurry of research publications in the aeronautical, mechanical, and marine fields, now deemed branches of engineering science; textbooks in engineering science began to appear; Macmillan's *Engineering Science Series* (1922) included works on electrical engineering and telephony.

R. V. Southwell, Jenkin's successor at Oxford, launched a prestigious Oxford Engineering Science Series in 1932. Southwell's career neatly illustrates the ironies of engineering science in practice. In an anti-industrial academic environment, he offered a small group of students "essential scientific equipment" in the form of systematic theoretical knowledge of idealized engineering systems. Worried that more and more research took place in government labs or large firms, he wanted to enhance the fragile reputation of academic engineering. He taught that engineering science was not the key to industrial success; it used mathematics and physics, but unlike them, considered practical material constraints, approximate (and, increasingly, computable) solutions, matter in bulk, and visualizable models. In Oxford, at least, engineering science was a research end in itself.

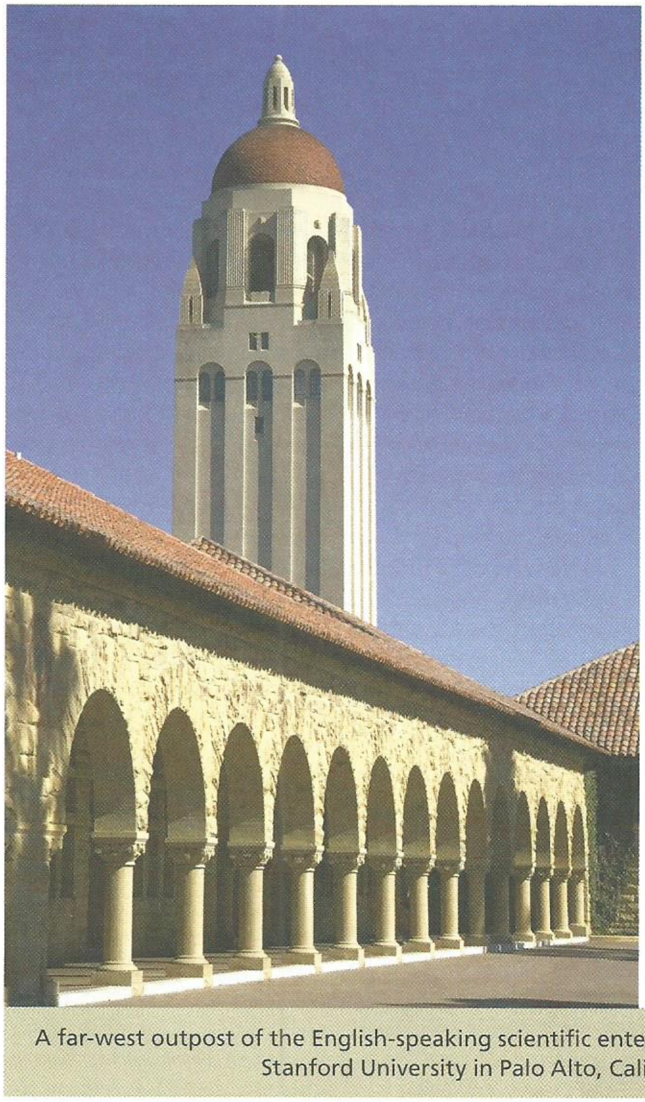
BEN MARSDEN

ENGLISH-SPEAKING WORLD. Science has had several principal languages over the centuries—Greek, Latin, Italian, Arabic, Chinese, French, German, and English. During the eighteenth century, French dominated discourse about natural knowledge. During the late nineteenth century, German became the principal scientific language for a large area including, besides Germany itself, Austria-Hungary, Sweden, Denmark, the Netherlands, and parts of Switzerland. Japanese who wished to pursue a career in medicine had to know German; so did citizens of the United States and Imperial Russia. English supplanted German to become the world-wide means of communication in commerce and travel as well as in science. The so-called "English-speaking world"—Britain, the United States, Australia, New Zealand, Ireland, most of Canada, and large enclaves elsewhere—has the great advantage of possessing this universal language as its mother tongue.

Britain's Legacy

Although during the nineteenth century, the British Isles produced extraordinary achievements in science—as indicated by the names Charles Darwin, Charles Lyell, James Clerk Maxwell, and William Thomson—and natural science had established a secure foothold in the other English-speaking countries, Germany was the leader in world science around 1900. Thanks in part to the work of Justus von Liebig at Giessen from the late 1820s, the Germans had become the unchallenged leaders in chemistry, both in the academy and in industrial applications. Britain's precocious William H. Perkin founded the aniline dye industry in the late 1860s, but Germany's stronger institutional base in applied science allowed it to capture the manufacture of all synthetic organic dyes. German higher education seemed equally strong. The twenty-eight German-speaking universities in central Europe, mostly located in Germany itself, had no parallel in the world in 1900. With their many distinguished professors, excellent laboratories, and easy accessibility, the German institutions drew students from all over the world, including significant numbers from the United States and Britain.

Against this array, Britain had the ancient universities of Cambridge and Oxford, the old Scottish universities, Trinity College, Dublin, and a rising number of municipal or



A far-west outpost of the English-speaking scientific enterprise: Stanford University in Palo Alto, California "red brick" institutions, notably the universities of London, Manchester, and Liverpool. McGill University, the University of Toronto, three small institutions of higher learning in New Zealand, and four universities of modest size in Australia represented the higher education available in the English-speaking parts of the British Empire. The United States had begun copying the German academic model with the establishment of Johns Hopkins in the 1870s, the University of Chicago in the 1890s, and the importation of an embryonic research ethic into the older East Coast institutions. The Land Grant Act of the Civil War years had established universities that would become research centers, notably in the Middle West and California. MIT was a modest engineering school; Cal Tech did not exist.

Partly in response to the German ascendancy, England debated the mission of its established universities, the role of research, and the place of experimental science in them. Cambridge had long excelled in mathematics, but until 1851, no course of study leading to a degree in chemistry or physics existed at Cambridge or Oxford. That year, Cambridge created the Natural Science Tripos (examination), which, however, long had a second-class standing in the university. Dirtying their hands with experimental work still grated on the sensibilities of Oxford dons, who regarded chemistry as "stinks." External pressures for change from political leaders, industrialists, and British scientists with German academic degrees had aroused strong opposition. The situation for natural science was much more favorable at the red-brick universities, especially the University of London, whose BSc degree could be obtained by examination even by non-resident students.

A concerted movement for sweeping changes in the ancient universities gathered momentum after 1870. The Devonshire Commission, led by William Cavendish, Duke of Devonshire, undertook a six-year investigation (1870–1876) into the state of British science. Scottish institutions came off well; the members of the Commission praised William Thomson's program in physics at the University of Glasgow, despite his master-apprentice approach to instruction. But the Commission harshly criticized conditions in England. It recommended the enhancement of existing resources and several new initiatives: eleven new chairs for science at Oxford, a National Ministry of Science and Education, a new astronomical observatory, a redirection of collegiate fellowships away from the Classics and toward the natural sciences, and a program of grants for research by established scholars to be administered by the Royal Society.

For the rise of the English-speaking countries in science, a particularly important initiative from the 1870s was the founding of the Cavendish Laboratory at Cambridge. The Duke of Devonshire served as Chancellor of Cambridge while chairing the reform commission. A descendant of two leading physical scientists (Henry Cavendish and Robert Boyle), Devonshire had excelled in mathematics as a student and had considerable experience in the iron and steel business. His financial contribution, more than sufficient to build and equip the laboratory, set a new standard of support for science in an academic setting. The first Cavendish Professor of Experimental Physics, James Clerk Maxwell, started a tradition of excellence that under his successors made the Cavendish for half a century what Niels Bohr called the center of physics.

Lord Rayleigh, successor to Maxwell as Cavendish director, received a Nobel Prize in physics in 1904 for his discovery of argon. In 1906, Rayleigh's successor, J. J. Thomson, received a Nobel for his discovery of the electron. Between 1895 and 1898, the New Zealand-born Ernest Rutherford worked with Thomson at the Cavendish on X-ray induced conductivity in gases. The work for which Rutherford received the Nobel Prize for chemistry in 1908—his development of a modern theory of radioactivity—took place at McGill University in Canada. Rutherford succeeded Thomson as Cavendish Professor and Laboratory Director in 1919.

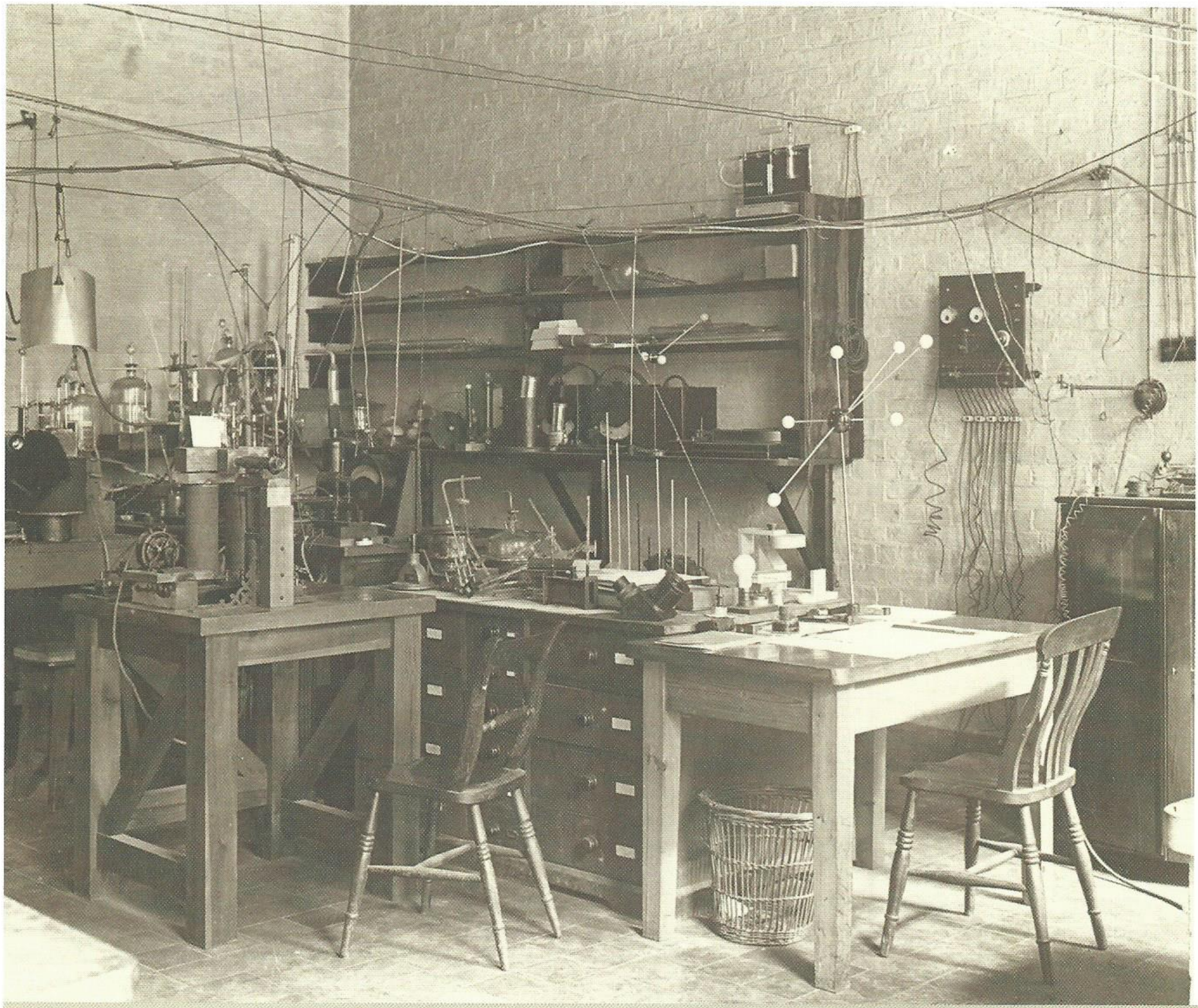
Impact of World War I

When war broke out in August 1914, science and engineering students in Germany numbered about 16,000; in Britain, 4,000 at most. A 1910 estimate put the number of working British industrial chemists at one-third the number working in Germany. Germany was spending three times as much on its universities as Britain. Britain depended on Germany for imports of dyestuffs as well as tungsten for making steel, pharmaceuticals, magnetos, certain kinds of optical glass, and, to some degree, even explosives.

In the United States, surging immigration, industrialization, and economic expansion had created a favorable environment for the growth of science at the beginning of the century. John D. Rockefeller's fortune made possible the establishment of the University of Chicago in 1891; unlike the East Coast institutions, it emphasized graduate education from the start. In 1901, the United States Congress created the National Bureau of Standards and authorized it to conduct research deemed necessary to establish appropriate standards for industry; a prominent physicist was named its director. An unprecedented gift of $10 million from Andrew Carnegie resulted in the creation of the Carnegie Institution of Washington. Other industrialists founded Stanford University, Vanderbilt University, and the Rockefeller Institute for Medical Research in New York.

World War I initiated the rise to preeminence of the English-speaking countries in science, partly because the war ruined Germany's economy, but mainly because it accelerated institutional developments that might otherwise have been delayed. In 1914, Britain created the British Dyestuffs Corporation, and the following year set up what became the Department of Scientific and Industrial Research (DSIR) and encouraged the formation of Research Associations to offset deficiencies in applied science made all too apparent by the war. The DSIR survived the war to continue government support to science. In 1916, a Committee on the Neglect of Science, chaired by Lord Rayleigh, launched major initiatives directed at the creation of a scientifically more literate public. Although the United States did not enter the war until 1917, it had moved in the same direction, creating the National Research Council (NRC) in 1915, letting research contracts to twenty-one university laboratories, and undertaking research on optical glass and chemical weapons. The performance of applied science during the war caused many firms in Britain and the United States to set up or expand industrial research laboratories after the war.

Southern California first became prominent in science just after the war when George Ellery Hale, one of the creators of the NRC and director of the Mt. Wilson Observatory, persuaded local industrialists that the region should have a major research university with forward-looking programs in science. Hale's recruitment of several distinguished faculty members, together with the large endowment pledged by his business supporters, made possible the conversion of the small Throop Polytechnic Institute (founded 1891) into the California Institute of Technology in 1921, with R. A. Millikan



A room at the Cavendish Laboratory in Cambridge, England, where many people from around the English-speaking world studied—notably the New Zealander Ernest Rutherford (1871–1937), who became the laboratory's director in 1920

as its founding president. Science and engineering in Canada, already strong at McGill from private benefactors, gained ground and reputation at the University of Toronto. There, with the active collaboration of Charles Best and help from J. J. R. Macleod and James Collip, Frederick Banting isolated insulin from the pancreas and demonstrated its effectiveness in treating diabetes. In 1923, Banting became the first Canadian to receive a Nobel Prize in physiology or medicine.

Just before the war ended, the Allies took steps to isolate German science. Delegates meeting in London in the fall of 1918 voted to dissolve the International Association of Academies, founded in the 1890s and headquartered in Berlin, and create a new International Research Council (IRC) from which citizens of the former Central Powers were excluded. The IRC finally admitted Germany in 1926. In the interim, Germany had not ceded its leadership. Despite the policy of the IRC, able young Americans such as Linus Pauling and J. Robert Oppenheimer went to Munich and Göttingen to study quantum theory.

The English-speaking countries had three advantages that would gain them eventual leadership across the sciences: numbers, resources, and a language that enabled them to function as a single, large community of scholars. The point may best be made by pointing to migration within the community. British-style education throughout the Empire had long allowed colonials to study or work in Britain. Thus did the eminent medical clinician and researcher, William Osler, born and educated in Canada, later teach in Britain (1904–1919). Similarly, Rutherford, after taking his degree at Canterbury College in New Zealand (1894), went to study at Cambridge. The travel went both ways. In 1885, William Henry Bragg, a protégé of J. J. Thomson's at Cambridge, moved to Australia and taught physics at Adelaide until 1909, later returning to Leeds in England. His son, William Lawrence Bragg, born and educated in Australia, became Cavendish Professor of Physics at Cambridge in 1938.

The pace of these movements began to increase during and immediately following World War I, as a result of improved transportation and more opportunities in research. Born and educated at Capetown in South Africa, Max Theiler studied medicine at the London School of Tropical Medicine from 1916 to 1922; he then worked in the United States at Harvard, the Rockefeller Institute, and Yale. Also during World War I, India's great mathematician Srinivasa Ramanujan from Madras visited Britain and became a Fellow of Trinity College, Cambridge, before returning home. Frank McFarlane Burnet, born in Australia in 1899 and educated at the University of Melbourne, studied at the Lister Institute in

London, then returned home. And in the 1930s, both Subramanyan Chandrasekhar from India and John Eccles of Australia studied in England, at Cambridge and Oxford, respectively. Chandrasekhar became professor of astrophysics at the University of Chicago after his years in England.

Eccles's career shows particularly well the career possibilities available to a scientist in the English-speaking world. Born in Melbourne in 1903, he studied and taught at Oxford from 1925 to 1937, directed a research institute in Sydney from 1937 to 1943, then moved to New Zealand's University of Otago. From 1952 to 1966, Eccles served as professor of neurophysiology at the Australian National University, Canberra, after which he moved to Chicago, and later Buffalo, New York. Other colonial systems—those of the French, the Dutch, the Spanish, and the Americans—also produced patterns of this kind, though none on anything like the scale of the British.

The Migration From Germany

Adolf Hitler's accession to power in Germany in 1933 completed what World War I had begun, preparing the way for the supremacy of the English-speaking countries in science. Following the enactment of the Nuremberg Laws later that year, most Jewish scientists were forbidden to work in Germany's universities. Those who could leave gradually left Germany, more often than not for Britain (Max Born) or the United States (James Franck). Albert Einstein had left Germany in 1930; he and several other distinguished European scientists became members of the Institute for Advanced Study in Princeton, a private institution founded earlier that year by the family of Louis Bamberger, a department store magnate.

Science in the United States was deeply enriched by the European immigrants. The physicist Maria Goeppert Mayer, a protégé of Max Born's at Göttingen, came in 1930 as the wife of an American chemist, Joseph Mayer. Naturalized in 1933, Goeppert Mayer taught physics at several institutions, often without compensation. One was the University of Chicago, a leading center for physics after the arrival of Enrico Fermi and Edward Teller, themselves exiles from Fascism and Nazism. Goeppert Mayer's presence at Chicago led to a position at the nearby Argonne National Laboratory, where she noted the existence of periodic properties for nuclear isotopes and their resemblance to electron shells in atoms. This work culminated in her shell model of the nucleus, for which she shared a Nobel Prize in 1963 with Hans Jensen and Eugene Wigner. In 1935, Hans Bethe arrived from Germany by way of a two-year position at Bristol in England. From his position at Cornell as professor of physics, Bethe moved to Los Alamos, New Mexico, where he played a leading role in the Manhattan Project to develop the atomic bomb. A consummate statesman of science, as well as a brilliant researcher, Bethe received an unshared Nobel in 1967, partly for his studies of energy production in the sun and other stars.

Nor was it only physics that benefited from the influx of European scientists. Though trained originally in theoretical physics, Max Delbrück—a great-grandson of Justus von Liebig—came to the United States in 1937 on a Rockefeller Foundation fellowship, switched to viral genetics, and investigated bacteriophages at several institutions. He shared a Nobel Prize in physiology or medicine in 1969. Fritz Lipmann, a biochemist, arrived in 1939. Another Rockefeller Foundation fellow, he held positions at Cornell, Harvard, and the Rockefeller Institute (renamed Rockefeller University). Lipmann became interested in metabolism and the enzymes that aid in digestion. He shared a Nobel Prize in 1953 with another German émigré, Hans Krebs. Krebs is notable as one of a significant but smaller number of scientists fleeing Nazi persecution who found opportunity in Britain, as opposed to the United States. Others—Otto Frisch, Rudolf Peierls, and Franz Simon—made suggestions that were instrumental in committing Britain and the United States to the atomic bomb project.

Postwar Science

Despite its much smaller scientific community and more modest funding base for research, Britain continued to attract talented foreign and domestic investigators in the postwar period. In 1951, the young American biologist James. D. Watson arrived at the Cavendish Laboratory after completing his Ph.D. at Indiana University. At Cambridge, he met and began working with a somewhat older British colleague, Francis Crick. In pursuing their classic work on the structure of DNA, they took full advantage of opportunities and information produced in the English-speaking world. In 1944, Oswald Avery of Columbia University had argued that DNA was the genetic material of bacteria. Essential knowledge of amino acids came from Erwin Chargaff of Columbia, whom Watson and Crick met in Cambridge; Rosalind Franklin, Maurice Wilkins, and Raymond Gosling at the University of London supplied X-ray diffraction photographs of DNA; Linus Pauling of Cal Tech suggested a clever but mistaken model of the DNA molecule that Watson and Crick improved on. The foundation of molecular biology, like the cooperation on the atomic bomb and many other episodes in science and technology in the twentieth century, was a product of interactions in the English-speaking world.

The United States, with its large land base and growing wealth, in some ways after 1900 duplicated the institutions of the British Empire (later British Commonwealth) within its own borders. In the pursuit of science, as in the acquisition of wealth, the American academic system, and to some degree the Canadian, were founts of opportunity. These nations created effective systems of universities and government and industrial laboratories, eager for competent staff irrespective of their national origins, readily open to one another, yet intensely competitive in a national context. Innovations historically successful in one institution—especially universities—were usually copied in others. In this sense, the fifty leading research universities of North America have something in common with the German universities of 1900. The industrial research laboratories have their parallels in the old dyestuffs industries, and the national laboratories a pale antecedent in the famous German bureau of standards, the Physikalische-Technische Reichsanstalt.

Ironically, the factor that underlay the hegemony of the English-speaking countries in science—a common language—has created a more even playing field for the rest of the world. Nearly all scientists now communicate in English, except with native speakers of their own language. That makes possible large transnational collaborations and migrations for study and research. An ever more tightly knit Europe, whose scientists communicate in English and sometimes enjoy support approaching American levels, has challenged the supremacy of the English-speaking nations, or rather of the United States, since Britain sometimes belongs to Europe, and Europe sometimes speaks English. Asia should not be left out of the equation. To take one straw in the wind, in the 1990s, Ken'ichi Fukui, Japan's first Nobel laureate in chemistry, was able to attract postdoctoral fellows from the United States and other countries because all shared the common language of English.

JAMES BARTHOLOMEW

ENTOMOLOGY. Entomology (along with ornithology) was one of the first fields of natural knowledge to professionalize. Men with specialist knowledge in the area were among the earliest of scientific employees in museums. Enthusiastic input from collectors, illustrators, travelers, and specialist taxonomists buoyed interest. During the seventeenth and early eighteenth centuries, insects featured in microscopical researches like those of Marcello Malpighi and Robert Hooke. Theologians and naturalists alike praised the beauty and complexity of insects, many seeing them as evidence for the wisdom and perfect design of God's works. Religious symbolism and entomological description joined in other ways: Jan Swammerdam explained insect life cycles in *The Natural History of Insects* (1737) as signifying Christ's resurrection. At the same time, the social insects, such as ants, bees, and wasps, provided civic metaphors, as in Bernard Mandeville's *Fable of the Bees* (1714), which proposes an idealized structure for human society. Notions about the efficiency of the hierarchical castes in ants' nests or beehives, and the concept of many individuals working for the general good, appeared in many philosophical tracts and utopian fictions. Moral lessons had long been found in locust plagues and the like. Insects also had economic value, as exemplified by the cochineal beetle, which, for several centuries, provided the primary source for red dye.

Many important entomological collections were founded and expanded during the eighteenth century. New techniques and devices for catching specimens, including nets, traps, and lamps, and conventions for adequate preservation and display, were developed. Insect collections, like those of shells or minerals, amused the wealthy, intrigued the learned, and provided financial opportunities for specimen hunters, shopkeepers, and book publishers. The publication of illustrated manuals boomed, complemented by catalogues and lists of identifying names. Specialist classification schemes—especially divisions of day fliers from night fliers, and beetles and bugs from butterflies—were introduced. Carl Linnaeus identified seven insect orders (today, twenty-nine are generally recognized). Insects played a key role in systems of physicotheology, such as Linnaeus's scheme of natural economy, which adumbrated the concept of a food chain. The relative number of organisms and the balance, or harmony, between them depended on insects as an essential source of food for birds. William Paley, in his discussion of the "polity of nature" in *Natural Theology or evidences of the existence and attributes of the deity* (1807), argued that the usefulness and beauty of insects counterbalanced their stings and bites. The curious reproductive patterns of some insects such as aphids aroused great scientific and philosophical interest. For much of the century the word "insect" was applied indiscriminately to most small organisms.

In Great Britain, an Entomological Society was founded in 1833 by a small group of enthusiasts—associated with an entomological club and periodical—who broke from the Zoological Society. The new society rapidly became a locus for expert taxonomic work, publishing scientific *Transactions* from 1834. In Paris and elsewhere, specialist taxonomists were also producing many detailed studies of individual genera or families.

A number of unusual classification schemes appeared in the early nineteenth century, most notably William Macleay's quinarían system (based on grouping genera and families in fives)—a significant attempt to reveal meaningful affinities and relationships between insects. Macleay's system was developed further by William Swainson. Parasitic insects were recognized by him as either highly complex or very reduced in structure when compared to the basic type to which they were related. This recognition allowed him to classify many organisms previously difficult to place. Identification of the various stages of insect life was also a focus of research throughout the century. Concepts of host organisms for different stages of the cycle, and insects as vectors of disease, were introduced, although they were not codified until much later.

The spontaneous generation controversy—centered around the debate between Louis Pasteur and Félix-Archimède Pouchet—demonstrated the importance of distinguishing between asexual (parthenogenetic) forms of reproduction, as displayed by aphids and other organisms, and sexual reproduction; and of establishing the mechanisms that underlay fertilization and cell multiplication. In Great Britain, the natural historical approach predominated. Sir John Lubbock, the Victorian politician and banker, began his career as a talented entomologist. Aided by advances in histological techniques and microscope optics, he described several key stages of the reproductive process in insects, tracing the "germ cells" through the generations. He later observed social behavior, perhaps inventing the glass observation hive in the process, and wrote the best-selling *Ants, Bees and Wasps* (1882). In the early twentieth century, Austrian biologist Karl von Frisch went further, investigating the routes taken by bees in search of food and the "dance" by which they communicated information to others in the hive.

Charles Darwin devoted much time to studying the mutual dependency between insects and flowers, the one acquiring food or nectar and the other achieving cross-fertilization. Darwin's results on the respective adaptations developed by both sets of organisms appeared primarily in *The Effects of Cross and Self fertilisation* (1876) although he had included much original matter on the subject in his *Orchids* (1861). He based his notion of the mutual dependency of insects and flowers on a tract published by Christian Konrad Sprengel in 1793. Notwithstanding the fanfare about apes and angels following publication of Darwin's *Origin of Species* (1859), evolution was best demonstrated by the insect world. In the 1860s and 1870s, Henry Walter Bates's and Fritz Müller's demonstrations of various forms of mimicry, in which palatable insects mimic unpalatable ones or inanimate objects like leaves in order to survive, gave strong support to evolutionary theory. Henry Bernard Davis Kettlewell's study of industrial melanism in moths and their differential survival rates ultimately substantiated modern evolutionary theory. Insects also proved crucial for genetic research, especially into mutation and recombination of chromosomes. Thomas Hunt Morgan deliberately chose the fruit fly for his laboratory work because of its rapid breeding, convenient maintenance, adaptable external characteristics, and large, easily observable chromosomes. In a few years the species was acknowledged as a highly suitable organism for experimental work. Much of Morgan's achievement, in fact, rested on having chosen an appropriate organism for the job. Other insects, particularly weevils, were similarly important in early population genetics and ecological modeling in the laboratory, as in Charles Elton's seminal work *Animal Ecology* (1927).

Insects are a significant factor in the medical health field, particularly epidemiology. Alexandre Yersin established fleas as the causative agent in plague in the 1880s. Alphonse Laveran saw the malarial parasite in human blood while working in Algeria in 1880; Patrick Manson identified the mosquito as the parasite's customary host, or vector (1894); and Ronald Ross disclosed the malarial life cycle in 1897. Throughout the twentieth century pest control—for both medical and agricultural purposes—focused on programs of insect extermination, often with powerful insecticides like DDT.

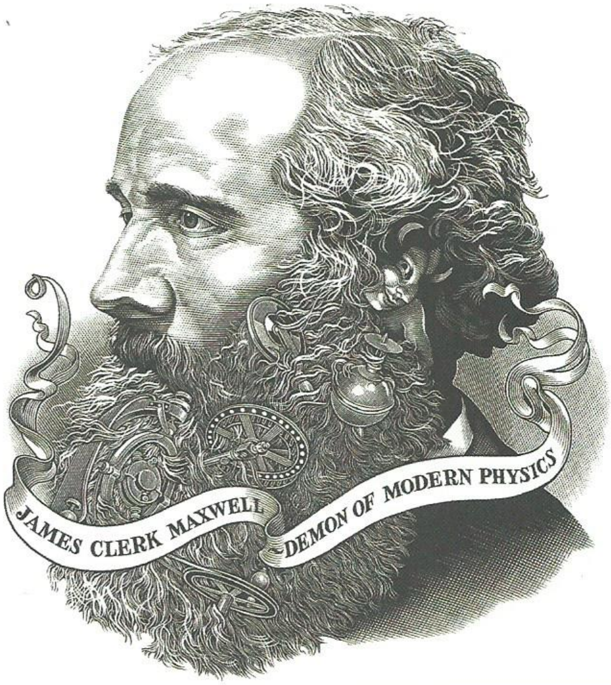
Janet Browne

ENTROPY. Many physicists and chemists quip that the second law of thermodynamics has as many formulations as there are physicists and chemists. Perhaps the most intriguing expression of the law is Ludwig Boltzmann's paraphrase of Willard Gibbs: "The impossibility of an uncompensated decrease in entropy seems to be reduced to improbability."

Entropy owes its birth to a paradox first pointed out by William Thomson in 1847: energy cannot be destroyed or created, yet heat energy loses its capacity to do work (for example, to raise a weight) when it is transferred from a warm body to a cold one. In 1852, he suggested that in processes like heat conduction, energy is not lost but becomes "dissipated" or unavailable. Furthermore, the dissipation, according to Thomson, amounts to a general law of nature, expressing the "directionality" of natural processes. The Scottish engineer Macquorn Rankine and Rudolf Clausius proposed a new concept, which represented the same tendency of energy towards dissipation. Initially called "thermodynamic function" by Rankine and "disgregation" by Clausius, in 1865 the latter gave the concept its definitive name, "entropy," after the Greek word for transformation. Every process that takes place in an isolated system increases the system's entropy. Clausius thus formulated the first and second laws of thermodynamics in his statement "The energy of the universe is constant, its entropy tends to a maximum." Hence, all large-scale matter will eventually reach a uniform temperature, there will be no available energy to do work, and the universe will suffer a slow "heat death."

In 1871, James Clerk Maxwell published a thought-experiment attempting to show that heat need not always flow from a warmer to a colder body. A microscopic agent ("Maxwell's demon," as Thomson latter dubbed it), controlling a diaphragm on a wall separating a hot and a cold gas, could choose to let through only molecules of the cold gas moving faster than the average speed of the molecules of the hot gas. In that way, heat would flow from the cold to the hot gas. This thought-experiment indicated that the "dissipation" of energy was not inherent in nature, but arose from human inability to control microscopic processes. The second law of thermodynamics has only statistical validity—in macroscopic regions entropy *almost* always increases.

Boltzmann attempted to resolve a serious problem pointed out by his colleague Joseph Loschmidt in 1876, and by Thomson two years earlier, that undermined the mechanical interpretation of thermodynamics and of the second law. This law suggests that an asymmetry in times dominates natural processes; the passage of time results in an irreversible change, the increase of entropy. However, if the laws of mechanics govern the constituents of thermodynamic systems, their evolution should be reversible, since the laws of mechanics are the same whether time flows forward or backward: Newton's laws retrodict the moon's position a thousand years ago as readily as they predict its position a thousand years from now. Prima facie, there seems to be no mechanical counterpart to the second law of thermodynamics. In 1877, Boltzmann found a way out of this difficulty by interpreting the second law in the sense of Maxwell's demon. According to Boltzmann's calculus, to each macroscopic state of a system correspond many microstates (particular distributions of energy among the molecules of the system) that Boltzmann considered to be equally probable. Accordingly, the probability of a macroscopic state was determined by the number of microstates corresponding to it. Boltzmann then identified the entropy of a system with a logarithmic function of the probability of its macroscopic state. On that interpretation, the second law asserted that thermodynamic systems have the tendency to evolve toward more probable states. A decrease of entropy was unlikely, but not impossible.



James Clerk Maxwell (1831–1879) with some mechanical devices in his beard. The "demon" refers to a thought experiment he devised to probe the second law of thermodynamics.

In 1906, Walther Nernst formulated his heat theorem, which stated that if a chemical change took place between pure crystalline solids at absolute zero, there would be no change in entropy. Its more general formulation is accepted as the third law of thermodynamics: the maximum work obtainable from a process can be calculated from the heat evolved at temperatures close to absolute zero. More commonly the third law states that it is impossible to cool a body to absolute zero by any finite process and that at absolute zero all bodies tend to have the same constant entropy, which could be arbitrarily set to zero.

Theodore Arabatzis And Kostas Gavroglu

ENVIRONMENT. In the nineteenth century, human exploitation of the natural environment came to be recognized in the industrializing West as a threat to human welfare. Romantics deplored the destruction of forests as diminishing the world's esthetic and spiritual reserves, and scientists warned that forest depletion entailed losses in watershed and habitats for numerous plant and animal species. The outcry led the governments of Germany and France to embark on programs of forest restoration and preservation. In the United States, the concern for forests joined with the realization that the fron-

Rachel Carson (1907–1964), US biologist and writer, with her book, *Silent Spring* (1962), a classic in the environmental movement

tier was closing to create a "conservation" movement, which flourished from the 1890s through the 1910s and made its overarching goal the maintenance of the nation's natural heritage. Championed by President Theodore Roosevelt, the movement won the creation of national parks, forest preserves, and laws for the protection of wildlife.

The American environmental movement lost force during the turn towards probusiness conservatism in the 1920s, but concern for the preservation of nature revived under the reformist leadership of President Franklin Roosevelt in the 1930s and drew renewed support after World War II. Spreading affluence permitted people the time and means to visit the national parks and to find in the unspoiled beauty of nature spiritual relief from the sameness of the suburbs, television, and fast-food restaurants.

The environmental agenda was significantly enlarged when, in 1962, Rachel Carson, a trained biologist and gifted writer, published *Silent Spring,* a powerful dissection of the intricate and myriad ways that herbicides and pesticides, particularly DDT, were poisoning man and nature. Carson called the chemicals of weed and insect control "elixirs of death," explained that they killed wildlife, especially birds, as they accumulated in the wild food chain, and stressed that they threatened human health. In 1972, the federal government banned the use of DDT. In the meantime, *Silent Spring,* which was widely translated, had helped to stimulate a worldwide environmental movement with the goals of protecting nature and health against the threats of poisonous pollutants entering the air, earth, and water.

In the late 1980s, scientists warned that environmental dangers global in scope had arrived. The growing commercial and industrial use of chlorofluorocarbons (CFCs) was depleting the upper atmosphere's ozone layer, which blocks the passage of cancer-causing ultraviolet light from the sun. The burning of fossil fuels was releasing enough carbon dioxide to create a greenhouse-like effect that raised average temperatures around the globe. The clearing of the tropical rain forests was destroying large fractions of the world's species of insects, birds, and animals.

In the Montreal Protocol (1987) and its toughened revision (1990), the industrial nations agreed to limit the use of ozone-depleting gases. At Rio de Janeiro in 1992, they reached an accord in principle to reduce the production of greenhouse gases below the levels of 1990; and in Kyoto in 1997, they devised tentative mechanisms for achieving that goal. However, in 2001 the United States, which produces one-quarter of the world's greenhouse gases, withdrew from the Kyoto Protocol, declaring that the required limits on the burning of fossil fuels would injure its economy. A comparable commitment to indigenous economic growth in Latin America has interfered with attempts to slow the destruction of the rain forests.

DANIEL J. KEVLES

ERROR AND THE PERSONAL EQUATION. Since Greek times astronomers have recognized that observations were afflicted by errors, that results based on them might only be approximate, and that the quality of data varied. Astronomers in early modern Europe took the first steps toward giving reliable estimates of those errors. Johannes Kepler, who used Tycho Brahe's observations to derive the elliptical shape of planetary orbits, was probably the first to construct a correction term that assigned a magnitude to error, and among the first to give a theory of an instrument (the Galilean telescope) for purposes of improving the accuracy of measurements taken with it.

During the eighteenth century, steps were taken toward standardizing the analysis of measurements and understanding the conditions under which different sets of measurements could be combined. Analysts identified two types of errors: constant (affecting the instruments or the conditions of measurement) and accidental (randomly affecting the quality of the measurements themselves). Control over instrumental errors was achieved at first by codifying the behavior and demeanor of the observer, by taking into account the limitations of the human senses (especially vision), by examining how outside sources contaminate experiments, by perfecting the construction of instruments, and by developing methods for instrument calibration.

The second type of error, the random, relates to classical probability theory. Initially the criteria for the selection of good measurements rested mainly on the notion that the median or the mean of measurements reduced the effect of errors in any of them. In 1756, the mathematician Thomas Simpson countered reports that a single well-taken measurement sufficed by demonstrating the superiority of the mean; his presentation to the Royal Society of London included a discussion of the equal probability of positive and negative errors and an argument that the mean lies closer to the true value than any random measurement. But no consensus existed about the selection or combination of measurements. The first firm parameters of an error theory emerged from the consideration of observations of the Moon's motion, especially its libration; from secular inequalities in the motions of Jupiter and Saturn; and from measurements of the shape of the earth. During the second half of the eighteenth century, Johann Tobias Mayer, Leonhard Euler, Rudjer J. Bošković, and Johann Heinrich Lambert developed ad hoc, limited, varied, but effective procedures for combining measurements made under different conditions. In 1774, Pierre-Simon Laplace deduced a rule for the combination of measurements using probability theory.

The meridian measurements made during the French Revolution to determine the new standard of length, the meter, gave the occasion to devise the first general method for establishing an equilibrium among errors of observation by determining their "center of gravity." This method, the method of least squares, was so employed in 1805 by Adrien Marie Legendre. In 1806, Carl Friedrich Gauss acknowledged Legendre's work but only to say that he had been using the method for years. A priority dispute ensued. Three years later Gauss published the first rigorous proof of the method of least squares; he demonstrated that if the mean is the most probable value, then the errors of measurement form a bell curve (Gaussian) distribution. The true value (which has the smallest error) lies at the center of the distribution, while the width of the curve determines the precision of the measurement. (Application of the method assumes the absence of constant or systematic errors.) From astronomy the method spread to chemistry, physics, mineralogy, and geodesy. It was also applied to practical projects including the reform of weights and measures, longitude determinations, triangulations, the U.S. Coastal Survey, and cadasters, where it set the boundaries within which dispute could take place. The method of least squares made large-scale projects, like Gauss's magnetic map of the earth, manageable by providing a means to combine and assess data from geographically dispersed locations. Over the course of the nineteenth century, the method dominated error analysis (especially in the German-speaking world) and shaped the development of probability theory.

The power of the method of least squares seemed to eradicate the subjective element in the treatment of measurements. But Gauss and his colleague the astronomer Wilhelm Olbers acknowledged in 1827 that sometimes measurements displayed large deviations from the mean. When was the deviation large enough to justify ignoring a measurement? Gauss could not provide an objective answer and recommended reliance on intuition. In 1852, Benjamin Peirce developed a rigorous method for rejecting outliers.

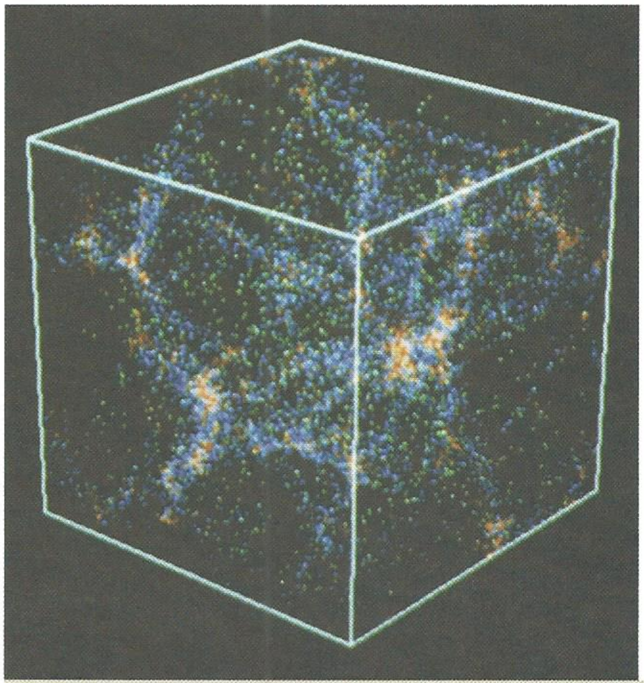
Deviations of another sort led Friedrich Wilhelm Bessel to develop the personal equation. In 1823, he noted a constant difference in the measurements taken by the former British Astronomer Royal Nevil Maskelyne and his assistant, which Bessel referred to physiological differences. With the "personal equation" Bessel calculated the average difference between two observers; he could then combine measurements taken by several observers. The personal equation created the factory-like atmosphere of nineteenth-century astronomical observatories where teams of observers were calibrated according to its principles. It was seldom used elsewhere except in psychology. Especially in Wilhelm Wundt's physiological institute at Leipzig, the personal equation became the foundation of a research program in the determination of human reaction times.

The history of error and the personal equation embraces far more than the history of rules and methods. The determination of error is always an estimate; were the true error known, perfectly accurate results could be attained. Because reliable estimates of error generate confidence in results, the history of error theory also sheds light on how trust is established in a scientific community and beyond. In the teaching laboratory, the method of least squares indicated how well student investigators performed an experiment, and thus the level of expertise they had attained. In practical fields like surveying, the introduction of the method aided professionalization. Finally, the method of least squares shaped the moral economy of the sciences by promoting honesty in the execution and reduction of observations. Proper application of the method became a sign of the investigator's integrity.

Kathryn Olesko

ETHER is a possibly nonexistent entity invoked from time to time to fill otherwise empty spaces in the world and in natural philosophy. Descended from the Aristotelian quintessence, which occupied the realms through which the planets wandered, and the Stoics' pneuma, which held the world together, ether characterizes theories opposed to atomism, which admits spaces void of matter. Both sorts of theories—plenary and atomistic—enjoyed vigorous revivals during the Scientific Revolution. With the invention of the barometer and air pump in the middle decades of the seventeenth century, void and ether became objects of experiment and, in practice, very much the same (no)thing.

The experimental investigation of void began above the mercury in the barometer tube. This space had the property of transmitting light and magnetic virtue, but not sound, and of allowing the free passage of bodies through it. It seemed infinitely compressible or, rather, was so subtle that it could pass right through glass. Were these the properties of a space void of all matter or of one filled with a substance different from ordinary matter? A third way, preferred by René Descartes, made the special substance and ordinary matter the same thing, except for the size and shape of their constituent parts. Isaac Newton countered with a solution as hard to grasp as ether itself. In his world system, the planets move through resistanceless spaces replete with the presence of God and perhaps also with springy ethers that mediated gravitational attraction, chemical behavior, electricity, mag-



Computer simulation of a portion of the universe containing 10,000 galaxies. They tend to cluster in filaments, walls, or massive nodes, leaving large voids (or expanses of ether) where the density is virtually zero.

netism, and the interaction of light and ordinary matter. These ethers, unlike the Stoics' pneuma and Descartes' plenum, admitted voids among their particles.

With the acceptance of the wave theory of light in the nineteenth century, physicists felt obliged to suppose the existence of a subtle, imponderable medium whose undulations constituted the disturbance perceived as light. The first mathematicians to attempt a detailed picture of this "luminiferous ether" modeled it as a mechanical substance with rigidity and inertia. They managed thus to represent most of the properties of light—reflection, refraction, interference, and polarization. As William Thomson (Lord Kelvin) and the Cambridge mathematician George Gabriel Stokes explained it to other model-makers, the luminiferous ether had to combine the properties of shoemakers' wax, which allows slow bodies to pass through it under steady pressure but shatters when struck a sharp blow, with those of rigid steel, which can support transverse vibrations without suffering permanent distortion.

The ether soon became so familiar that mathematicians assimilated it to ordinary matter, or vice-versa. As latter-day Cartesians, they pictured atoms and molecules as permanent vortex rings in an all pervasive ether (Kelvin, following a hydrodynamical theory of his friend Hermann von Helmholtz, and Joesph John Thomson) or as knots or twists in it (Joseph Larmor). This sort of modeling was a specialty of physicists who had passed through the honors course in mathematics at Cambridge (the mathematical tripos). Continental physicists, especially the French, regarded it with a mixture of puzzlement and distaste. Nonetheless, James Clerk Maxwell devised an ether model for the mediation of electrical and magnetic forces that suggested that light was an electromagnetic phenomenon.

Maxwell's theory charged the ether with accounting for electricity and magnetism as well as for light. None of the several models with mechanical properties proposed to effect it succeeded. Hendrik Antoon Lorentz and others then introduced space-filling media that had nonmechanical properties in order to underpin an adequate electrodynamics of bodies moving through the suppositious ether (relativity). In 1905, Albert Einstein showed the value of discarding the ether as a substrate and reference frame for electrodynamic phenomena.

The acceptance of relativity theory, however, did not destroy the ether. Einstein himself, in his application of relativity principles to the gravitational theory (1915), supposed that a gravitating body distorts nearby space, and that these distortions determine the trajectory of a passing ponderable body. An entity that can distort its shape, deflect light, and propagate electric and magnetic disturbances can be called a void only by discourtesy. More recently, quantum electrodynamics has filled the void with a vacuum that undergoes energy fluctuations and acts as a theater for the creation and annihilation of virtual particles. One such fluctuation is said to have given rise to the present universe. Physicists appear to need an ether on which to load all the properties of the physical world they cannot otherwise explain. Ether, alias the vacuum, exists. Void is anything but nothing.

J. L. Heilbron

ETHICS AND SCIENCE. Even if it is possible to distinguish, it is no longer possible to dissociate science from its practical applications, which often raise ethical questions. The interaction of ethics and science has always been reciprocal, but until the end of the nineteenth century, science mostly posed challenges for ethics, while in the twentieth century ethics posed new challenges for science.

"Ethics" derives from the Greek word for "character," and the Greeks and Romans assumed that if we knew the human good or could model our behavior on that of a virtuous person, ethical conduct would be natural. Christian medieval ethics added aristocratic mutual obligation and contract, the divine inspiration of natural law, and the moral fallibility of all human beings. By the seventeenth century, new knowledge was generating new forms of power, as recognized by Francis Bacon, which meant new potential for wealth, abuses, and corruption. The mechanistic division between mind and matter in the work of René Descartes, which implied irrelevance of ethical issues to natural knowledge, was denied by Baruch Spinoza's equally rationalist *Ethics*. The various scientific academies established by the early eighteenth century stressed an ethics of mutual reliability among their members as free-acting observers.

Echoing the Greco-Roman model, the story of Galileo's conflict with the church, his prosecution and recantation under duress, and the ultimate vindication of his ideas has often been taken by scientists as a parable of the need for integrity and autonomy in scientific research. Scientists have had no direct analog to the Hippocratic Oath's injunction to "do no harm," but have taken as normative Galileo's insistence on following and finding the truth about this world in the face of convention and orthodoxy. The arguments of scientists have thus been suffused with a moral subtext of struggle against entrenched authority, constructing new knowledge not only in their own interests but in the interest of humanity.

During the eighteenth and nineteenth centuries, idealizations of science became entwined with the Enlightenment promise of human progress and the norms of reason. Impressed by the success of natural philosophy, Immanuel Kant laid out ethical claims revolving around an autonomous, rational agent. His (agent-based) "categorical imperative" to treat the humanity of others not simply as a means but as an end in itself stemmed from his understanding, in contrast to his skeptical contemporary David Hume, of logically consistent thinking as essential to our human nature. In (consequence-based) utilitarian ethics, science was modeled differently, becoming the root of cost-benefit analyses that offered the greatest good for the greatest number. Since science increasingly was associated with new developments in medicine, engineering, commerce, and warfare, the ethical systems represented by Kant and the utilitarians played ever greater roles in thought about how humans should treat each other. The nineteenth-century social sciences emerged in this climate, striving to treat human relationships as objects of study in order to better them. But when George Edward Moore published his *Principia Ethica* in 1903, he cordoned off reason from moral claims on the grounds that the "good" was fundamentally indefinable in natural terms. His contemporary Max Weber also stressed the distinction between fact and value, reinforcing Hume's argument that no bridge spanned the gulf between "is" and "ought." The impact of science on ethical thought had reached an impasse.

During the twentieth century, influence shifted to the impact of ethical thought on science, particularly physics, chemistry, and the life sciences, as the sciences themselves became entrenched authority for many people. Amid the moral chaos engendered by the trauma of World War I and the world economic depression of the 1930s, scientists made themselves increasingly important for military, economic, and medical advances. Robert K. Merton noted that this fact produced among scientists renewed calls for the autonomy, integrity, and insulation of science, but at the same time brought ever more anxious and insistent demands that science incorporate the ethic of social responsibility. The demands sometimes came from scientists themselves, sometimes from citizens galvanized by specific technological developments, and sometimes from governments responding to their publics. Following World War II, demands for responsibility coalesced into movements and various professional codes of behavior. As the country with the greatest resources and influence in science, the United States was often a barometer of these developments.

With the advent of the Cold War and the nuclear arms race, physicists and other scientists in every militarily powerful nation faced tensions between pursuing new knowledge and limiting its dangers. Some scientists who helped develop nuclear weapons led efforts to limit their further use, founding journals, creating federations, informing public opinion, and advising or critiquing governments and policies. These tensions and perplexities animated the Pugwash Conferences begun in 1957 in the Nova Scotia village by that name, at which scientists from around the world met as private individuals to discuss ways to limit international strains caused by the multiplication and increasing deadliness of armaments. As the philosopher Hans Jonas has observed, the first ethical responsibility in our era is to help insure that the possibility of ethics persists, that our creations do not destroy our world.

The importance of chemistry for new materials, agriculture, pharmaceuticals, energy, and many other factors in an elevated standard of living has raised a host of ethical concerns related to social justice and the environment. The same chemical production processes that give us new materials and energy generate pollution. New herbicides and pesticides that increase food production also have negative run-off effects on the environment. Drugs such as antibiotics have undesired evolutionary impact on microbes. All of these involve financial costs beyond the reach of much of the world's population, at a human price these people often bear. Soon after the publication of Rachel Carson's book *Silent Spring* (1962), the American Chemical Society enunciated the "Chemist's Creed" (1965), pledging an ethic of responsibility to the public, science, chemical profession, employer, self, employees, clients, students, and associates. The Green Revolution in agriculture produced a backlash against monocultures in favor of biodiversity, especially in the non-Western world, and the environmental ethics movement has modified or redirected significant scientific resources and programs. Many people have argued that ethical systems may not be universally valid, but ethical concerns must be global.

World War II was also a watershed in the life and social sciences, as Nazi eugenics policies and experiments on captive human beings led to postwar trials in Nuremberg. The ten principles known as the Nuremberg Code (1947), which emphasize the informed, voluntary participation of human subjects and safeguards for their welfare, became the basis for a sequence of declarations by the World Medical Assembly and most ethical discussions of human experimentation. By 1966, in the United States, written informed consent and harm/benefit assessments had to be submitted to formal ethical review before research on human subjects could be conducted with funding from the National Institutes of Health. These considerations spread to other agencies, cre-

Mehr Geld für Jugendfreizeitheime!
Hannover
DEMOKRATEN
F.D.P.-Mitglieder gegen Nachrüst
Entweder wir schaffen die Rustung oder die Rustung schafft uns ab
OHNE RÜSTUNG
Göttingen
KNACKT DEN ROTSTIFT
RUSTUNGSSTOP
Wir wollen wieder
IHR ZUVERLAESSIGES BESTATTUNGSINSTITUT
USAUSSR
BRD
CDUSPDFDPCSUDGB

Antinuclear demonstration in Germany. The banner at the bottom, center left, reads, 'Break the Red Pencil / Stop the Arms Race'.

ated a demand for a new specialty of bioethics, and altered research in the social sciences.

In the late 1960s climate of distrust of the role, direction, and authority of science in human affairs, geneticists and other biologists considered whether they were confronting ethical issues analogous to those facing physicists at the dawn of the nuclear age. After a brief, voluntary moratorium on certain lines of work, biologists agreed at the Asilimar Conference of 1975 upon a set of biological and physical safeguards in research on recombinant DNA and a set of ethical guidelines for informing staff of the possible hazards involved. Soon afterward, Peter Singer's book *Animal Rights* (1975) sparked a movement to extend to animals ethical protections similar to those afforded human subjects in research, some of which the American government put into place by the end of the 1980s. Anthropologists faced intensified disputes over the norms for study and disposition of human remains.

The growth of international corporate financial interest in genetic research in the 1980s and U.S. government funding for the Human Genome Project (1991) raised new ethical issues of ownership and privacy of genetic information, as well as new clinical, public health, and civil rights concerns. The HGP therefore decided to devote some of its funding to an Ethical, Legal and Social Implications Program. At the same time, the convoluted and politically controversial charges of scientific fraud in the decade-long David Baltimore case indicated the heavy-handedness of government policing of scientific integrity. Cloning technologies, stem-cell research, defensive research on biological weapons, and programs in robotics and artificial intelligence (which has given rise to a machine-rights movement) indicate that new bioengineering and bioethical issues will continue to proliferate.

Change fostered by science has been occurring too rapidly for many people and institutions to assimilate. Science and its technologies are implicated in the tensions between Western and non-Western values. Science played its role in the colonial expansion of Europe, and is closely associated with technological and medical practices that conflict with indigenous ethical and cultural assumptions. The ethical implications of the global impact of nuclear threat, environmental degradation, and bioengineering have raised the question of whether scientists can—or should—remain individual, free-acting agents of change.

ALAN BEYERCHEN

EUROPE AND RUSSIA. The main countries of Europe (including Great Britain and European Russia from time to time) have followed a similar pattern in developing the sciences since the second half of the nineteenth century. The attitudes of the dominant churches and the rate of commercial and industrial development have variously affected the pace and intensity of the pursuit of natural knowledge in the several countries. But the ready exchange of information, people, and inventions; the similarity of institutions for the study and spread of science; and commercial competition, warfare, and colonial adventures coupled development in the main European countries. The surprising finding that in 1900 the number of academic physicists per unit of population, and the amount of investment per unit of national income, were virtually the same in Britain, France, and Germany suggests the tightness of the coupling. This equalization occurred despite considerable differences in the methods of funding and the operations of the universities in the different countries.

During the eighteenth century the chief institutions concerned with natural knowledge divided their work in the same way throughout Europe: the universities taught established science, the academies sought new knowledge. The larger observatories and botanical gardens, often associated

The teaching laboratory in chemistry set up by Justus von Liebig (1803–73) at the University of Giessen (Hesse), as it appeared around 1840, when it drew workers from all over Europe with both universities and academies, taught, preserved, and developed their subject matters in the same way in Paris and Saint Petersburg. A flourishing book trade, expanding university libraries, and many review journals, some, like the *Göttingische gelehrte Anzeigen,* associated with universities, kept everyone interested abreast of the latest advances. European scholars saw themselves as inhabitants of a "republic of letters." The use of Latin and French as the languages of scholarly interchange, travel when war did not preclude it, the mobility of academicians (the moves of Leonhard Euler from Switzerland to Saint Petersburg to Berlin to Saint Petersburg, and of Pierre de Maupertuis from Paris to Berlin and back, exemplify the traffic), and the institution of "corresponding members" of the learned societies further enforced the notion of a pan-European communion of philosophers. Immanuel Kant's *Idea for a universal history with a cosmopolitan purpose* (1784) made a "universal cosmopolitan existence ... the highest purpose of nature." Ludwig Wachler, the author of a *History of history and art from the renewal of culture in Europe* (1812), taught that the cultivation of the sciences was a peculiarly European activity.

The sciences literally helped put Europe on the map. More exacting techniques for surveying and geodesy were developed in national academies, and academy expeditions helped establish the topographic contours of Europe. European governments learned to appreciate that precision measurement increased state revenues, and they set about the laborious task of establishing common units recognized beyond provincial boundaries. Enlightened states supported natural sciences for their utility; not only technical subjects like astronomy and geodesy with obvious applications, but also natural philosophy, geography, meteorology, mining, forestry, and agriculture, whose study would prepare better civil servants and effective policing.

Science unified more than knowledge and bureaucratic process. It helped constitute modern European states. Beginning in the early 1820s the Versammlung Deutscher Naturforscher und Ärzte brought together German-speaking physicians and naturalists from the patchwork of principalities, free cities, and palatinates that made up the region. The renowned explorer Alexander von Humboldt called its meeting in Berlin in 1828 "a noble manifestation of scientific union in Germany; it presents the spectacle of a nation divided in politics and religion, revealing its nationality in the realm of intellectual progress." The German institution spread—the European system was above all one of parallel institutional forms. In 1831 "gentlemen of science" founded the British Association for the Advancement of Science, which, like its German model, had a wide membership and moved to meetings around the country. The French counterpart came into existence just after the Franco-Prussian war exposed the error of not staying closer to the practices of its rivals.

By spreading French science, which already gave the tone to European science, the French Revolution marked the acme of the Republic of Letters; by having its way by force of arms, the Revolution simultaneously disseminated a republicanism that many scholars judged to be inimical to the old cooperative scholarship. Auguste Comte may have envisioned the approach of a "scientific" stage of human civilization in which the intellectual elites of Europe would form ties across political boundaries and initiate a peaceful "European revolution" (*Cours de philosophie positive,* 1830–1842). But he was too late—and too early. From the Napoleonic wars to the unification of Germany, rivalry rather than cooperation dominated the development of European scientific institutions. The main growth occurred in the universities and higher schools. The foundation of the University of Berlin in 1810 and the restructuring of elementary and secondary curricula in Prussia gave a strong impetus to the entire educational system. Research gradually became a responsibility of the professoriate and of their students who aimed to be secondary school teachers. The rationale became ideology: only those who had contributed to knowledge, however small the contribution might be, could transmit to others the right mixture of information and enthusiasm. The Germans invented the teaching laboratory, the research seminar, the disciplinary institute, and the Ph.D. After the middle of the nineteenth century, foreign students began to flock to the German universities, to profit from their professors and facilities and—helping to integrate the European system of science—to bring back home what they found useful and transportable. After their defeat in 1870–1871, the French sent a mission to discover what made German universities so strong. In consequence, the French strengthened their provincial faculties of science and set up new higher technical schools like the École Supérieure d'Electricité (1884) and the École Supérieure de Physique et de Chimie (1882).

The strength of the French educational system since the Revolution had been its technical schools. The École Polytechnique trained scientists and engineers in a great deal of higher mathematics combined with physics and chemistry. Its students, selected by competition, graduated to enter specialized engineering schools—for mining, civil engineering, artillery, and so on. They then practiced as state employees, civil or military. Along with the centralized École Polytechnique the Revolution created an École Normale Supérieure, which supplied the teachers for the new system of state secondary schools (the *lycées*). The excellence of the Parisian technical schools and the scientific culture they supported made France the mecca of European natural philosophers and mathematicians until the 1830s and 1840s. As late as 1845 William Thomson chose Paris as the best place to complete his education in physics.

Thomson had been educated in old British universities (Glasgow and Cambridge). By the time he went to Paris, a new sort of university, which emphasized modern languages and science, had begun to grow. The University of London was put together from University College and King's College, founded in 1826 and 1831, respectively; later other colleges were added. Provincial manufacturing centers supported the creation of "redbrick" universities, which trained practical scientists of the second industrial revolution. Beginning in the 1850s committees of Parliament forcibly brought Oxford and Cambridge into the nineteenth century by establishing professorships in science and reducing the power of the humanistic dons.

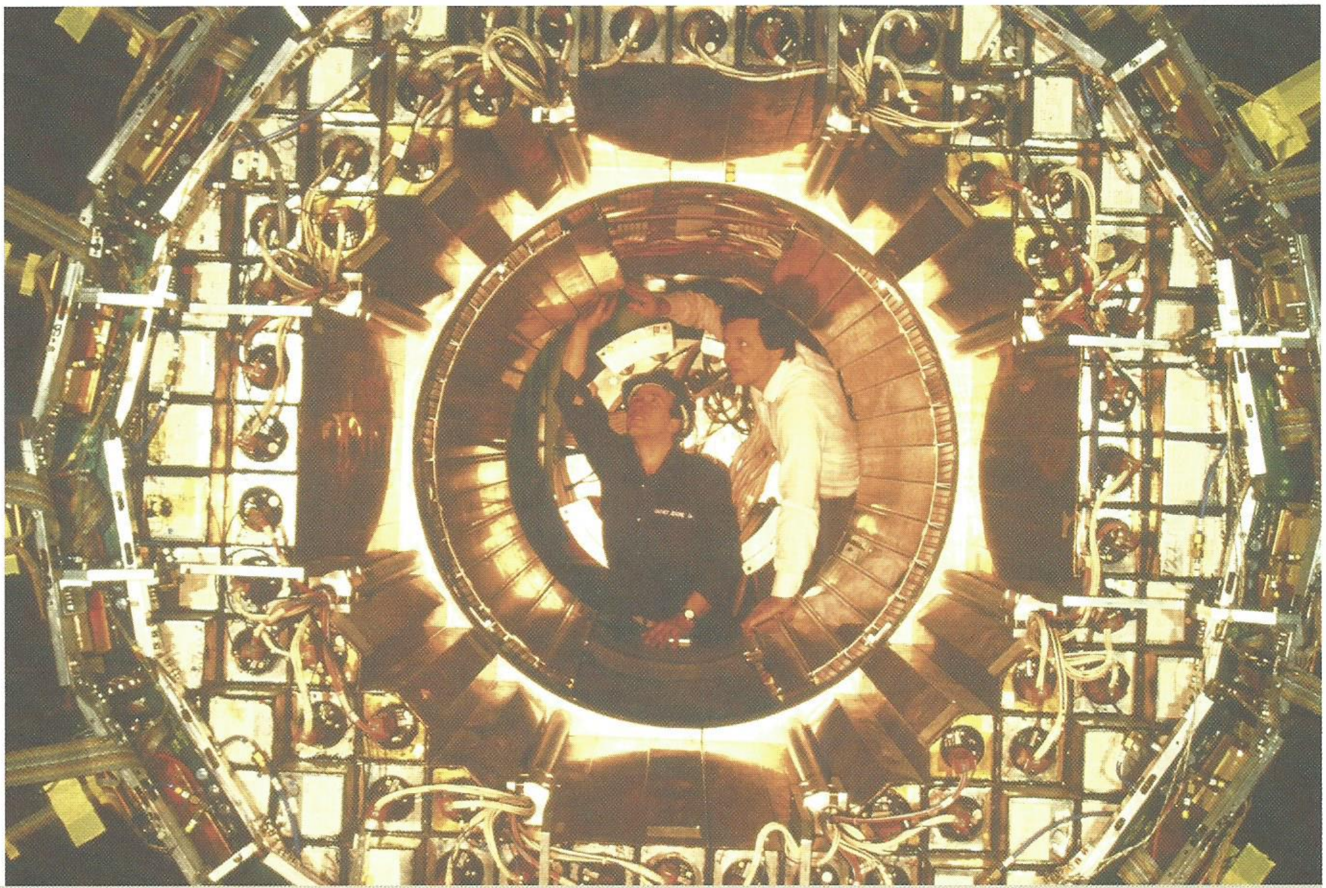
As rivalry and war propagated the stronger institutional forms from one country to another (the Germans borrowed from the École Polytechnique for their *Technische Hochschulen),* pressures from science and its applications forced the invention of new means of cooperation. Some, like the famous meeting in Karlsruhe in 1860 where chemists came to settle their differences over atomic weights, were fleeting. Others, like the International Bureau of Weights and Measures, established near Paris in 1875, have endured. The need for agreement over measures made an irresistible force for internationalism.

The push toward standardization, the increasing mobility of students, the ever more efficient distribution of scientific journals, the remarkable expansion of the applied sciences that marked the second industrial revolution—all of these factors contributed to a pan-European identity for science even as imperial rivalries reached their peak. In *A History of European Thought in the Nineteenth Century* (1896–1914), John Theodore Merz, a German with a doctorate on Hegel who ran a chemical factory in Britain, gave voice to the growing conviction that "in the course of our century Science at least has become international ... [W]e can speak now of European thought, when at one time we should have had to distinguish between French, German, and English thought."

Around 1900, the reconstruction of the Republic of Letters was cemented by the foundation of the International Association of Academies, with headquarters in Berlin; the International Catalogue of Scientific Literature, a retrospective inventory of periodical literature run from the Royal Society of London; and, outlasting both, the Nobel Institution and its prizes. On the nationalist level, the Kaiser-Wilhem Gesellschaft (founded 1911) copied in its own way the Royal Institution of Great Britain (founded 1799) and the Carnegie Institution of Washington (founded 1902), both examples of the use of private money for scientific research, then contrary to German practice. Alarmed British scientists pointed to Germany's expenditures on higher education to try to obtain, without much luck, greater resources from a stingy government. German scientists pointed to British trade schools and to the large expenditures on big research institutions made by the United States. French scientists pointed everywhere.

World War I shattered the growing internationalism. It replaced the International Association of Academies, headquartered in Berlin, with the International Research Council (IRC), dominated by the Belgians, French, British, and Americans, which did not admit the former Central Powers until 1926. The war also led to the creation of the Soviet Union, which was to spend most of the twentieth century outside the Western concert of science, and, indirectly, Nazi Germany, which would soon be ostracized for its hounding of Jewish academics. Still, World War I consolidated parallels among the belligerents: closer cooperation between science and the military and industry in the various countries, and, among the Allies, creation of equivalent institutions for the channeling of government money into academic science. The international Rockefeller philanthropies set up to support the exchange of researchers and to help build scientific institutes in Europe (France, Germany, Denmark, and Sweden were among the recipients) also helped the advanced scientific nations progress together.

After the opening of the IRC to the former Central Powers and the foundation of various international unions for pure and applied science, cosmopolitanism had a brief renewal. Just before the Nazi takeover, for example, the staff of sixty chemists at Fritz Haber's Kaiser Wilhelm Institut für Physikalische Chemie included seven Hungarians, four Austrians, three Russians, two Czechs, two Canadians, and one each from the United States, England, France, Poland, Ireland, Lithuania, Mexico, and Japan. During the late 1920s, international meetings increased in frequency. The Nazis and fascists then promoted internationalism in their special way by forcing some of the greatest European scientists to flee, particularly to Great Britain or the United States. At the same time, the Soviet Union drew in on itself. It had recruited left-leaning European scientists regardless of passport to help build up scientific research institutes in



Technician working on the OPAL particle detector at CERN (Conseil Européen pour la Recherche Nucléaire), set up by a consortium of European countries the People's Commissariat of Heavy Industry. The successive political purges of 1936–1938 expelled many visiting scientists, and the remainder left at the earliest opportunity.

World War II damaged the material infrastructure of European science and, together with the emigrations of the 1930s, made the United States by far the world's dominant scientific power. Soviet scientists who until the mid-1930s had played a lively part in multilateral European exchanges were sorely disappointed to find themselves further isolated by Cold War politics. Science remained an engine of prestige for the Soviet social experiment, however, and the growth in the Soviet Academy of Sciences in particular reflected its members' ability to turn the geopolitical insecurities of Soviet leaders into massive infusions of support for scientific research.

Two differences between Soviet and western European scientific institutions are especially notable. In Russia funding for individual programs of research did not come through formal independent peer review, but rather from large block grants to their host institutions. This practice exaggerated the discretionary powers of institute directors, who seldom resisted the temptation to cultivate huge patronage networks as the addition of classified research swelled the staffs of some institutes to a thousand or more. The Soviet Academy of Sciences also far outstripped its European counterparts in the control of institutional resources. In collective terms, it could thus dispense both resources and status, a function usually performed by separate institutions elsewhere.

Cold War rivalries and incipient European integration aided the rise of multinational laboratories. High-energy physics, with its unprecedented concentration of material and human resources on the search for the ultimate constituents of matter, took the lead. If the popular rationales for these expenditures often made reference to bilateral geopolitics, each new generation of accelerators still fostered increasingly complex multilateral collaborations. The best known institution in the western half of the continent was the European Center for Nuclear Research (CERN in its French abbreviation), founded outside Geneva in 1954 after arduous negotiations involving twelve sponsor nations. On the other side of the Iron Curtain, members of the Warsaw Pact nations joined Soviet physicists in building a rival accelerator at Dubna, outside Moscow, at an analogous institute—the Joint Institute for Nuclear Research.

Large-scale collaborations came to the life sciences with the founding of the European Molecular Biology Laboratory (EMBL) in the 1970s. Based in Heidelberg, it boasted four affiliated facilities elsewhere in Europe, and more than a dozen member nations. Where the lengthy lead times for particle experiments dictated a large permanent staff along with a steady stream of visiting researchers at CERN, EMBL had few permanent staff and visiting appointments lasting several years at most before the researcher returned to a home institution. It aimed not so much to transcend national boundaries by means of a single institution as to ensure steady cross-fertilization among the scientific communities of its member nations. Other initiatives like the European Synchrotron Radiation Facility (Grenoble), EURATOM, and the European Space Agency have been launched as well, with varying degrees of success.

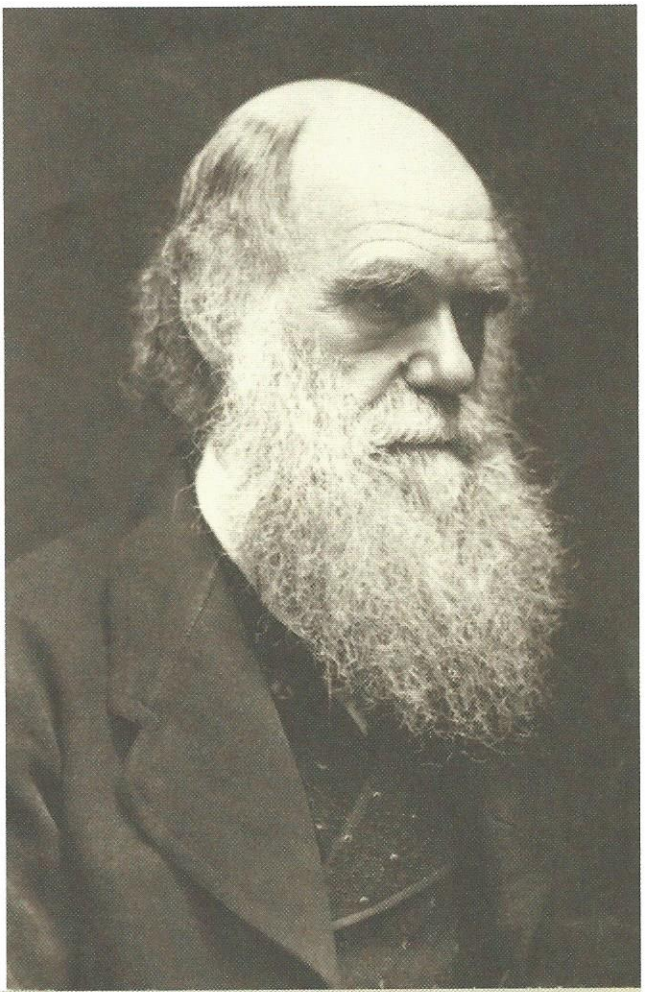
The collapse of the Soviet Union and the increasing federalization of the European Union have reshaped the playing field for science in Europe. Scientists from EU nations are among the primary beneficiaries of employment mobility across borders, and continuing economic disparities have also made it attractive for Russian, Czech, or Hungarian scientific elites to pursue careers further west on the continent. Science in Russia, though financially impoverished in general, shows modest signs of stabilizing after the "brain drain" of the early 1990s, with a pronounced shift toward grant-based research funded by private (both foreign and domestic) and government foundations.

France and Germany continue to fund large systems of institutes for pure research with few rivals elsewhere in the world, but more and more of the money for academic research passes through Brussels. Since proposals seem to have a better chance of success the larger the spectrum of collaborators, EU grants make a powerful force for the integration of European science. Nonetheless, the entire enterprise maybe regarded as underfunded, particularly in Britain. Both Japan and the United States spend half again as large a percentage of their gross domestic products on research and development compared to the average EU member. The increasing autonomy of European Council members vis-à-vis their national state bureaucracies, however, offers further opportunities for the scientists of Europe to cement broader institutional alliances that constrain national policy makers. European political union remains anything but certain, yet most scientists continue to claim "Europe" as one of the surest means (whether directly or indirectly) for the local advancement of science on a global stage.

Karl Hall

EVOLUTION. What we now call evolution in biology—the notion that organisms are related by descent—was first debated within the life sciences during the second half of the eighteenth century. The word "evolution," however, had been used in the seventeenth and eighteenth centuries to denote individual, embryonic development, not descent. "Evolution" (from Latin *evolvere,* "to unroll") then meant typically the unfolding of parts preexisting in the embryo, as conceived by the supporters of "preforma-tion" in embryology. Occasionally, supporters of epigénesis used evolution to denote what they regarded instead as the successive addition of new parts in individual development.

From the mid-eighteenth century—both jointly with earlier embryological speculations and independently of them—a number of natural philosophers formulated hypotheses implying a dynamic conception of the history of the universe, the earth, and life, as opposed to a static conception of nature. Stasis was then increasingly regarded, and occasionally attacked, as typical of the major western religious traditions. The Enlightenment produced new or renewed dynamic conceptions of nature: in astronomy, by attempts aimed at extending Newtonian concepts to explain the history of the planetary system as well as its functioning (Georges-Louis de Buffon, Immanuel Kant, Pierre-Simon de Laplace); in the earth sciences, by evidence pointing at a formerly unthought of antiquity of the earth (Buffon, James Hutton); and in the life sciences, by speculations on a possible temporalization of the traditionally static system of classification of living beings (Charles Bonnet, Jean-Baptiste Robinet), by attempts at formulating materialistic explanations of the origin of life, generation, heredity, development, and change of organic structures (Benoît de Maillet, Pierre de Maupertuis, Erasmus Darwin), by the occasional observation of variability in species (Carl Linnaeus), and by the transposition of the notion of embryonic development to the entire history of life on Earth (Carl Friedrich Kielmeyer).



Charles Darwin (1809–1882) British naturalist known for his theory of natural selection

Between 1802 and 1820, Jean Baptiste Lamarck combined several of these themes to produce the first systematic, if not always clear, theory of organic change (in those years "evolution" in its present meaning is documented only in the works of Julien-Joseph Virey). Around 1830, Etienne and Isidore Geoffroy Saint-Hilaire developed and circulated Lamarck's notions further. Charles Lyell discussed Lamarck's views from a critical perspective in his authoritative geological work of the early 1830s, where he used "evolution" for the first time in its present sense in English. Lamarckian notions, combined with speculations on embryonic development and the nebular hypothesis in astronomy, figured also in the first popular book to spread an evolutionary worldview in the English-speaking countries: Robert Chambers's anonymously published *Vestiges of the Natural History of Creation* (1844).

From 1859, Charles Darwin's *Origin of Species* attracted enormous attention to the issue of the natural derivation of all species from one, or few, original living forms. In scientific as well as popular circles the question at issue was "evolution." Darwin avoided the word, however, preferring the expression "descent with modification." The philosopher Herbert Spencer and many of Darwin's own followers preferred "evolution," because of its broad implications for a view of nature—often secularized, and embracing humankind and society as well as the cosmos—that emphasized gradual, progressive change, achieved through competition.

Darwin's own explanation of evolutionary change, the theory of natural selection (Darwinism), faced strong opposition even among knowledgeable scientists. The late nineteenth century saw many attempts to fill up the gaps ("missing links") of the fossil records documenting ancestral histories, and little agreement on the causes of evolution. Around 1900, neo-Darwinism, neo-Lamarckism, and orthogenesis competed with one another and other theories of evolutionary change.

After the rediscovery of Gregor Mendel's laws in 1900, it took about four decades for biologists from various specialties to build consensus around the so-called modern synthesis, or neo-Darwinian theory of evolution, combining Darwin's notion of natural selection with the science of genetics. Since the 1940s, that has been the evolutionary theory adopted by the majority of biologists. From the mid-1960s, however, new approaches have emerged to the study of biological evolution, deploying the tools and concepts developed in the meantime by evolutionary ecology, paleontology, and, especially, molecular biology. The study of evolutionary change at the molecular level, in particular, has become a major research field, and the results achieved have led to conclusions sometimes diverging from mainstream neo-Darwinian concepts.

For example, the circumstance that genetic variation (now measured with techniques like gel electrophoresis of enzymes) is occasionally uncorrelated with reproductive success and adaptive evolution—and thus seems "neutral" with regard to natural selection—has led some biologists, notably Motoo Kimura, to develop, beginning in 1964, the neutral theory of molecular evolution. The theory asserts that much of the evolutionary change observed at the molecular level occurs via random genetic drift, unaffected by natural selection.

On another, connected front, privileging the study of fossil evidence and the process of speciation, Niles Eldredge and Stephen Jay Gould began in 1972 to develop the hypothesis of punctuated equilibria, which departs from the neo-Darwinian notion of evolutionary change as gradual and continuous. The hypothesis asserts that the history of many fossil lineages shows long periods of little morphological change (stasis) alternating with brief periods of rapid change associated with speciation.

Since the 1960s, the issue of human evolution has also aroused renewed scientific interest. The frequent harvest of ancient fossil specimens, especially from Africa; the study of mitochondrial DNA, allowing tentative dating of the more recent branches of the human family tree; and the statistical assessments of genetic variation, favoring a comprehension of how biological and cultural traits may interact in human populations through migrations; have made and continue to make dramatic news in popular as well as scientific circles.

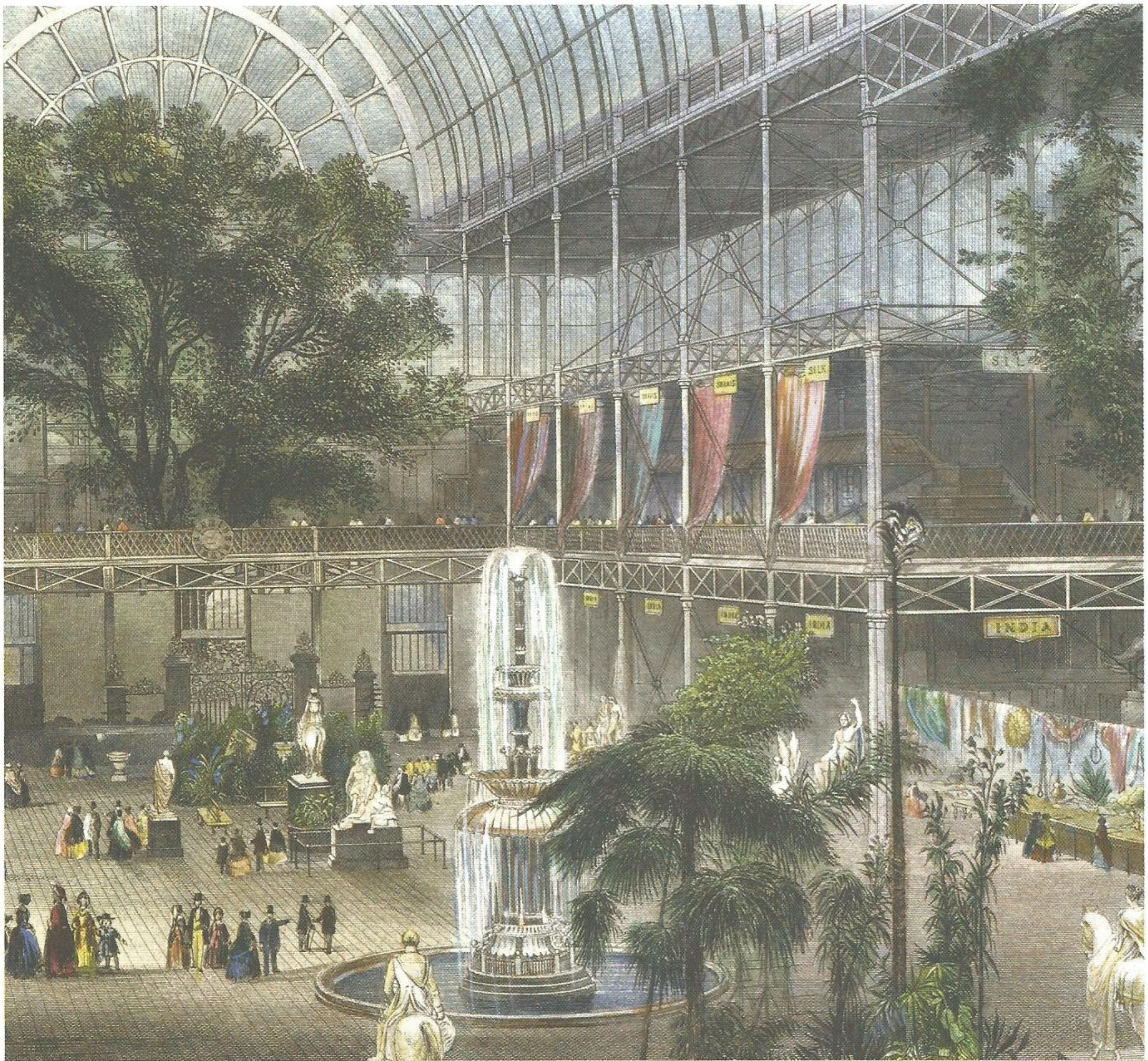
Despite the opposition called up repeatedly by phenomena like social Darwinism and its several twentieth-century derivatives, and because of the recurrent conflicts over the religious and ideological implications of our understanding of evolution, evolutionary biology continues to carry with it today all the excitement that accompanied the publication of Darwin's *Origin* in 1859.

Giuliano Pancaldi

EXHIBITIONS have shaped much of the cultural landscape of the modern world. Architecture and planning, mass entertainment and consumption, colonialism and imperialism, and not least, the cultures of science and technology owe much of their form and substance to the temples of modernity erected episodically throughout the world since the middle of the nineteenth century. Science suffused the very idea of exhibitions, their ideologies of progress, and the philosophies of classification that ordered displays. Exhibitions, moreover, diffused scientific ideas and introduced millions of people to scientific discoveries—radium and X rays, for example—and technological innovations—electric lighting, the telephone, plastics, and satellites. Scientists from different countries used exhibitions as a venue to meet and share their work and as a marketplace for instruments and technologies.

International exhibitions, also known as great exhibitions, universal expositions, and world's fairs, began with London's 1851 Crystal Palace Exhibition. The Great Exhibition of 1851, the brainchild of Albert, the Prince Consort, established the basic patterns of organization and display that would endure for decades without drastic modification. It built upon and to some extent supplanted traditions of local fairs and several decades of industrial displays at mechanic's institutes and national exhibitions in France and other countries. The success of the Crystal Palace Exhibition spurred other nations to follow suit, launching a veritable parade of international extravaganzas that Gustave Flaubert called "the delirium of the nineteenth century." By World War I nearly one hundred international exhibitions had been held around the world. The largest late-nineteenth-century exhibitions frequently received visitors numbering in the tens of millions, culminating in the Paris Universal Exposition of 1900, attended by some fifty million people. In the twentieth century, international exhibitions disappeared during both world wars, only to be revived afterwards, each time with diminished status and importance.

Prince Albert promoted the Great Exhibition of 1851 as a carousel of industrial progress, a liberal and free trade antidote to the climate of unrest that haunted Europe in the years around 1848. The exhibition would provide an illustration of how "the great principle of division of labor, which may be called the moving power of civilization, is being extended to all branches of science, industry, and art." The exhibition would become a "scientific experiment," Albert announced, an attempt to reveal human progress as an unfolding of God's natural laws and to further "a naturalist's insight into trades." For Albert, a disciple of the Belgian statistician Lambert-Adolphe-Jacques Quetelet, the experimental results would show themselves



The Crystal Palace during the Grand International Exhibition in Hyde Park, London, in 1851 in the system of classification of sciences, arts, and industries. Many scientists were consulted for the classification, including the biologist Richard Owen, the German chemist Justus von Liebig, and especially, the British chemist Lyon Playfair, who presided over the final system of classes and stipulated the conditions of selection and the procedure of juries.

Classification remained an emblem of the primacy of science and a central theme of debate in major exhibitions held around the world. Several major exhibitions experimented with radically different methods of classification. For the Paris Universal Exposition of 1867, for example, the French engineer and sociologist Frédéric Le Play devised a philosophical classification system that encompassed not only industry but the whole of human activity in a didactic arrangement linked with the architecture of the exhibition palace. Also noteworthy was the attempt of Harvard psychologist Hugo Münsterberg to deepen the philosophical content of the exhibition by subsuming the classification of the world's fair held in St. Louis in 1904 to the disciplinary principles of a vast international scientific congress held at the exhibition.

Juries remained the key institution of international exhibitions. Composed of international experts, frequently scientists, their judgments set the standard for every field of endeavor. Both the selection and judgments of juries were often contested and the debates contributed greatly to the emerging concept of the scientific or technological expert. The British scientist Charles Babbage, for example, suggested that the 1851 exhibitions jury be regarded as the prototype of a professional class of scientists. In practice, juries endlessly disputed the basic principles of evaluation. As a result, exhibition juries promoted the creation of modern international institutions of standard weights and measures.

At the Paris Universal Exposition of 1855, jury members, beset with headaches over how to test, compare, and classify objects of diverse national origin, signed a document imploring the authorities of all countries to participate in international negotiations to establish coordinated meteorological standards. Several countries signaled their support, and in 1867 an international commission was established to debate and implement the metric system as the international standard for science, technology, and commerce. In the decades that followed, numerous international scientific commissions used exhibition sites to hammer out standards agreements. The most famous of these, the international agreement on standards of electrical resistance, was reached by several delegations of scientists, including William Thomson, Lord Rayleigh of Britain, and Hermann von Helmholtz, Werner von Siemens, and Rudolf Clausius of Germany, at the International Electrical Exhibition of Paris in 1881.

Several features of exhibitions attracted scientific pilgrims to the throng. Exhibitions played host to international scientific congresses, bringing scientists into direct contact with colleagues from other countries. At these meetings, as with similar gatherings of artists, industrialists, and politicians, scientists were exposed to national differences in method, apparatus, and philosophy. Exhibitions also furnished scientists with the opportunity to see and buy scientific instruments from around the world and to display and sell instruments of their own design. As in the industrial trades, early exhibition promoters expressed the hope that science would benefit from the increased contacts between instrument makers and eminent scientists. This desideratum seems to have been met frequently; for example, the Astronomer Royal George Biddell Airy visited the 1851 exhibition to examine Charles Shepard's electrically driven master clock controlling slave dials elsewhere in the building.

The optimism about this type of exchange reached its apogee in 1876, when an international exhibition devoted exclusively to scientific instruments took place at London's South Kensington museum. Scientists and instrument makers (and their apparatus) from many countries mingled profitably. After surveying what was probably the most complete spectrum of scientific instruments ever assembled, British physicist James Clerk Maxwell composed a taxonomy of scientific apparatus according to their functions and principles of construction. Arraying the different components of physical and chemical apparatus in close analytical detail, Maxwell's "General considerations concerning scientific apparatus" was a perfect example of the "naturalist's insight into trades" to which exhibitions aspired but did not always produce.

By contrast, the broader attempt at science education that was part of every exhibition's mission delivered mixed results. The early exhibitions drew on their origins in mechanic's institutes and worker education movements to promote mass education and diffusion of science and technology. The early Victorians had become adept at "learning by seeing," at understanding the principles of steam engines and related machinery, tracing with the eye the visible processes of driveshafts, gears, belts, valves, pulleys, cutoffs, and levers that drove and transmitted power. Aiming at a similar clarity and directness, exhibition displays of various scientific disciplines including the physical sciences, as well as geology, biology, and anthropology, generally eschewed the grotesque imagery of earlier curiosity cabinets in favor of lucid, analytical depictions of objects and artifacts. Statistics featured prominently in exhibits of many kinds, offering a seemingly transparent representation of the hidden facts of nature and society.

Over the course of the nineteenth century, exhibition organizers and participants gradually pulled back from the more ambitious attempts at scientific content and created exhibits that used the results of science to dazzle, inspire, and impress. The visiting public turned out to be less avid and equipped for education than promoters hoped, and new kinds of edifying entertainment gradually supplanted rigorous instruction in the majority of exhibits. Historians have attributed this transition in part to the changing nature of science and technology themselves. Late-nineteenth-century science was increasingly dominated by electricity and other phenomena (such as X rays) whose operations were invisible and whose principles proved difficult to communicate. After 1876, when the wonders of the phonograph, telephone, electric lighting, loudspeakers, and electric railways prevailed at exhibitions, entrepreneurs like Thomas Edison exploited the dazzling character of the new technologies to enhance the prestige of their business enterprises. Such developments, coupled with a growing tendency of elite professional scientists to distance themselves from applied science or technology, contributed to a growing bifurcation between pure and applied science at exhibitions. While attempts to communicate elements of applied science remained, exhibitions witnessed an increasing renunciation of attempts to communicate the content of pure science, opting instead for aestheticized displays of general convictions.

Because the diffusion of science at exhibitions overlapped with other forms of popularization, it is impossible to precisely gauge their broader cultural impact. But there can be no doubt that the ideologies and aesthetics of exhibition displays have left a legacy in many of the characteristic modes of scientific popularization, including fascination with scales of magnitude, emphasis on visual communication, and promotion of the material bounty of scientific progress.

Robert M. Brain

EXTRATERRESTRIAL LIFE. Displaced from the center of Aristotelian cosmology, the earth became one of many planets in the Copernican worldview. Galileo Galilei's telescopic observations of earthlike mountains on our moon, and of moons circling Jupiter, emphasized this displacement. The principle of plenitude, which interpreted any unrealized potential in nature as a restriction of the Creator's power, argued for inhabitants on other worlds. Although there was no evidence of lunar inhabitants, why else, asked the English clergyman John Wilkins in his 1638 *The Discovery of a World in the Moon,* would Providence have furnished the moon with all the conveniences of habitation enjoyed by the earth?

Social critics seized on lunar inhabitants either as members of a perfect society or as exemplars of all earth's vices. This literary convention furnished some defense in attacks against the establishment and helped spread the idea of a plurality of worlds. So did persistent rumors that England intended to colonize the moon.

Life spread beyond the moon in the French astronomer Bernard de Fontenelle's *Entretiens sur la pluralitè des mondes* (1686). During their evening promenades, the conversation of a beautiful marquise and her tutor turned to astronomy. On the second evening they spoke of an inhabited moon, on the third of life on the planets, and by the fifth night they had progressed to the idea of fixed stars as other suns, giving light to their own worlds. More conventional astronomy textbooks repeated these views.

Belief in extraterrestrial life permeated much of eighteenth- and nineteenth-century thought. It allowed an easy attack on Christianity, whose teachings about Adam, Eve, and Christ might appear ridiculous if the earth were not the whole of the habitable creation. Similar concerns regarding the immensity of the universe and the corresponding insignificance of humans appeared in novels.

The gullibility of a public raised on pluralist writings is illustrated by the widespread acceptance of reports in the *New York Sun* in 1835, purportedly from Sir John Herschel at the Cape of Good Hope, detailing his observations of winged quadrupeds on the moon. *The New York Times* judged these reports to be probable.

Many aspects of the extraterrestrial life debate appeared in Percival Lowell's Martian hypothesis and in reactions to it. Too modest to believe humankind the sole intelligence in the universe, Lowell, a wealthy Boston investor, announced in 1894 his intention to establish an observatory in the Arizona Territory and search for signs of intelligent life on Mars. There was already in America a lively interest in Mars, attributed by cynics to public imbecility and journalistic enterprise. Others hoped that the discovery of intelligent life elsewhere would increase reverence for the Creator. Lowell reported an amazing network of straight lines, which he interpreted as canals, and concluded that Mars was inhabited. Astronomers criticized Lowell for seeing only the evidence that supported his beliefs. Many readers, however, were persuaded by Lowell's literary skill. They also applauded the social arrangements of Mars, as elucidated by Lowell, particularly the abolition of war.

Changes in scientific knowledge in the twentieth century strengthened belief in extraterrestrial life. Larger telescopes expanded the observable universe to millions of galaxies, each containing millions of stars, all rendering it increasingly improbable that our earth alone shelters life. In 1953, Stanley Miller and Harold Urey at the University of Chicago synthesized amino acids, the building blocks of life, from a mixture of methane, ammonia, water, and hydrogen, the supposed ingredients of our primitive earth's atmosphere. Although the late astronomer Fred Hoyle attributed both the origin of life on earth and much of subsequence evolution to showers of microorganisms from space, his was a minority view, though recently resurrected. Most scientists suppose that life occurs inevitably on earthlike planets, of which they estimate that millions exist in the universe. *Star Trek,* the television series, visits some of these planets every week.

Skeptics object that, if intelligent life is inevitable and has had billions of years to evolve and travel through the universe, it should long since have reached our earth. That extraterrestrials are not known argues against their existence. Believers in UFOs (unidentified flying objects) attribute the absence of evidence of extraterrestrials to a government cover-up.

The chemical theory of the origin of life coincided with the space age and did not long remain earthbound. In 1976, in one of the greatest exploratory adventures of the twentieth century, the National Aeronautics and Space Administration (NASA) landed two Viking spacecraft on the surface of the planet Mars, at the cost of over one billion dollars. Experiments detected metabolic activity, but probably from chemical rather than biological processes.

Post-Viking, interest shifted from micro-organisms to direct communication with interstellar intelligence. Several early radio pioneers, including Guglielmo Marconi in 1920, thought they detected radio signals from Mars. The most comprehensive interstellar communication program was NASA's Search for Extraterrestrial Intelligence (SETI). From a small and inexpensive research and development project during the 1980s, SETI emerged in the early 1990s as a hundred-million-dollar program. A targeted search for radio signals focused on some thousand nearby stars, while a second element of SETI surveyed the entire sky. Ridiculed as "The Great Martian Chase," even after changing its name to "High Resolution Microwave Survey" in a vain attempt to highlight its potential for basic discoveries in astronomy, SETI lost its government funding in 1993. A scaled-back version of the original targeted search has been continued with private funding.

Would intercourse with extraterrestrials be beneficial? Suppose that they were a cancer of purposeless technological exploitation intent on enslaving us, rather than benign philosopher-kings willing to share their wisdom? Even if they should be helpful and benign, superior beings would be menacing. Anthropological studies of primitive societies confident of their place in the universe find them disintegrating upon contact with an advanced society pursuing different values and ways of life.

Norriss S. Hetherington

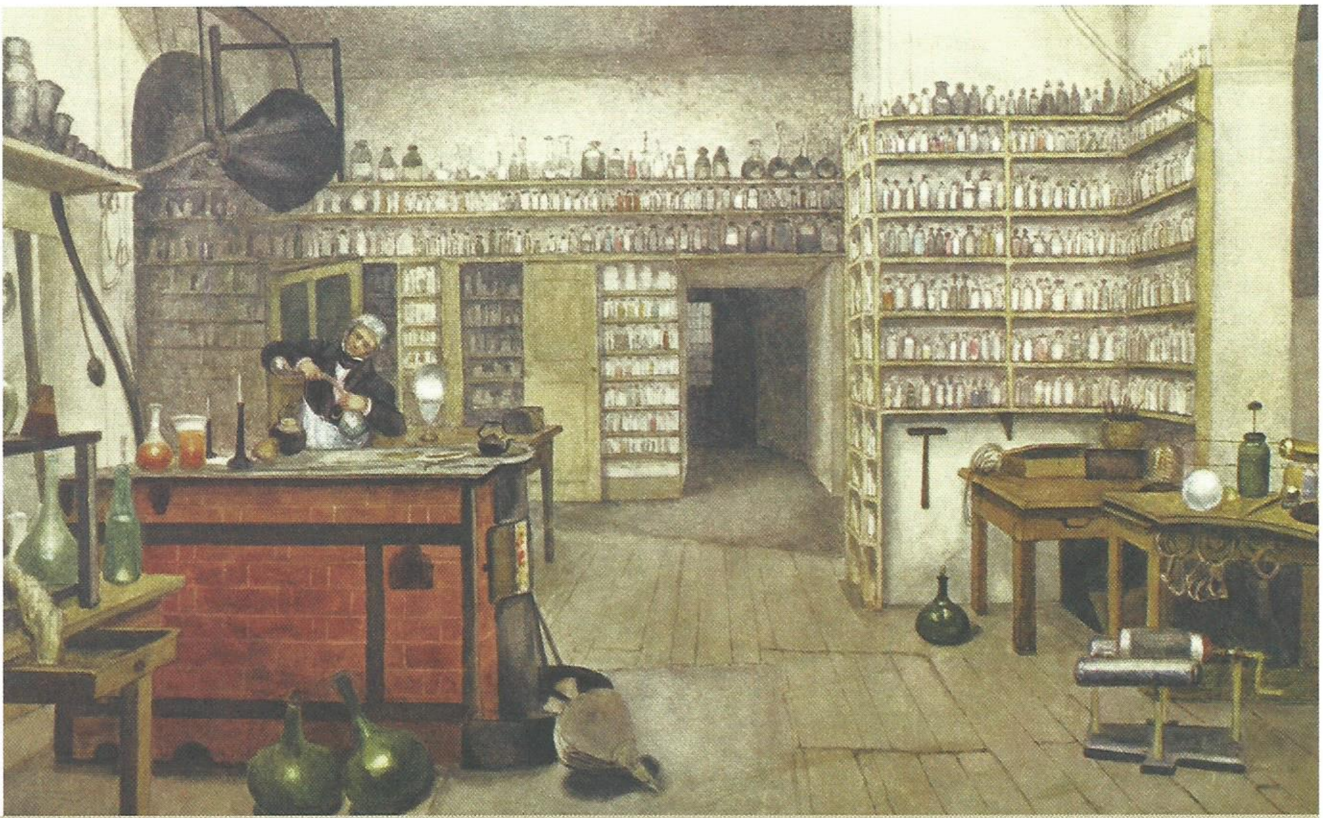
F

FIELD. The field, one of the most important concepts in modern physics, denotes the manner in which magnetic, electrical, and gravitational forces act through space. The field concept alleviated the difficulties many scientists found in assuming the existence of forces acting at a distance without the intervention of some material entity. Fields thus serve many of the functions of ether theories, which received their fullest development during the first half of the nineteenth century following the establishment of the wave theory of light by Augustin-Jean Fresnel.

Michael Faraday introduced the term "field" into natural philosophy on 7 November 1845, following his discovery of the magneto-optical effect and diamagnetism. He used the term operationally, in analogy to a field of stars seen through a telescope. During the next decade he developed the concept into a powerful explanatory framework for electromagnetic phenomena. This embodied much of his earlier thinking about the nature of magnetic action, especially his use of curved lines of force, which he had employed since the early 1830s to account for phenomena such as electromagnetic induction. It also embodied his opposition to conceptions such as atoms and the ether. As he wrote in 1846, he sought "to dismiss the aether, but not the vibrations."

Initially Faraday's contemporaries ignored his field concept, since it did not have the mathematical precision of action-at-a-distance theories such as André-Marie Ampère's electrodynamics. William Thomson (Lord Kelvin) reacted with contempt to Faraday's "way of speaking of the phenomena." However, Faraday's field theory had the great merit that in treating electrical events it took account not only of the wire carrying the electric current but also of the insulation of the wire, the surrounding medium, and so on. The notion of field made a good basis for developing a theory of long-distance telegraph signaling, which became a pressing problem in the mid-1850s with the intended construction of the transatlantic cable. Action-at-a-distance theories could not cope with this problem; Thomson, using Faraday's field concept, solved it.

This practical success prompted the adoption of the field concept in Britain. In the hands of Thomson and of James Clerk Maxwell it became a mathematical theory, much to the bemusement of the nonmathematical Faraday. However, unlike Faraday, who wished to abolish the ether from natural philosophy, both Thomson and Maxwell sought to interpret the field in terms of elaborate mechanical models (involving ethereal vortices) in an endeavor to retain the ether. This project ultimately failed. Relativity theorists such as Hendrik



Michael Faraday (1791–1867) in his laboratory in the Royal Institution in London

Antoon Lorentz and Albert Einstein replaced the ether by the nonmechanical field, a space capable of propagating forces, which is a cornerstone of modern physics.

FRANK A. J. L. JAMES

FIELD WORK. The histories and geographies of fieldwork and exploration are closely bound together in the development of modern science. During the fifteenth, sixteenth, and seventeenth centuries, both the logic of exploration and the consequences of its discoveries helped force a reconceptualization of the fundamental principles upon which scientific authority rested. Through the eighteenth, nineteenth, and twentieth centuries, exploration and fieldwork continued to be powerful forces in the shaping of science, although their main contributions had less to do with redefining principles of method than with developing substantive scientific knowledge of the world.

During the Age of Discovery (1450–1700), European nations, inspired by religious fervor and mercantile aspirations, developed a new understanding of the world beyond their own continent. Exploration in the Renaissance challenged established academic authority in three ways. First, the project of discovery, with its emphasis on the importance of experience, observation, and veracity, helped lay a new foundation for the production of knowledge about the world. This preeminently empirical form of knowledge acquisition threw into question the school philosophy with its emphasis on *a priori* reasoning, religious belief, and sedentary debate. However, this is not to say that Prince Henry the Navigator should be raised to the level of Nicholas Copernicus or Galileo Galilei as a hero of the Scientific Revolution.

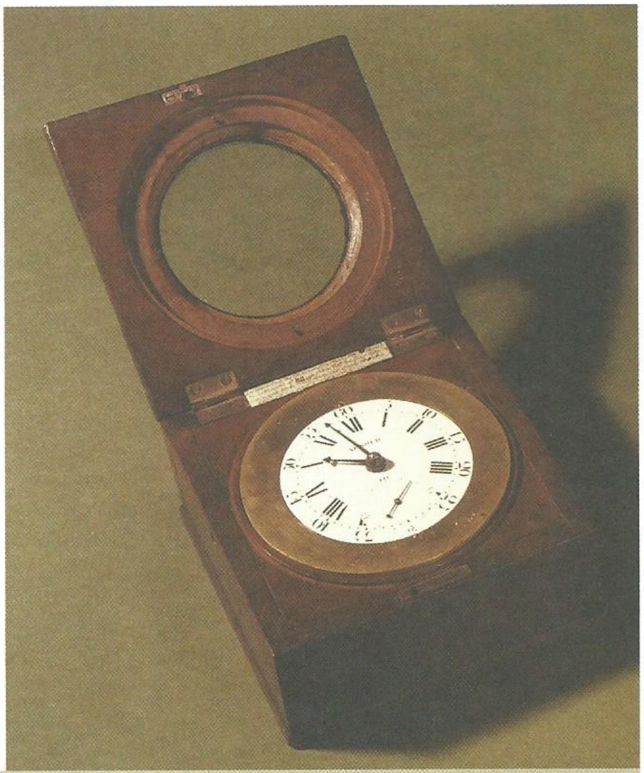
Second, the objects collected during voyages of discovery and the testimonies of respected observers on board ships revealed New World civilizations seemingly incompatible with Mosaic chronicles of creation. The unfamiliar environments of the Americas also challenged the established natural histories of the Old World. The representative natural history of the sixteenth century—for example, Konrad Gesner's *Historia animalium* (1551–1558)—promoted an associative understanding of animal life in which descriptions of animals included their mythological, etymological, cosmological, and iconographic relations, as well as their habits and characteristics. Not only did the creatures of the New World undermine the supposedly comprehensive Renaissance catalogues, but attempts at their inclusion within an emblematic natural history brought existing formats and classifications into question. How could one write a natural history of an animal knowing nothing about its name, iconographic associations, roles in human culture, relations to other creatures, or place in myths and legends? By the mid-seventeenth century, natural histories included the animals of the New World and dispensed with previous classical conventions.

Thirdly, Renaissance exploration challenged classical scholarship by its emphasis on application. For instance, Prince Henry the Navigator sought geographical knowledge. However, his voyages were also commercial, colonial, and religious in motivation. As new protoscientific techniques helped merchants and rulers establish empires of trade and dominion, so Europe's more radical natural philosophers argued that science should help improve the lot of humankind. The labors of some natural historians, mathematicians, chemists, and astronomers had a direct bearing on the endeavors of those involved in oceanic exploration. For instance, John Evelyn, a founding member of the Royal Society of London, advised the English Navy about the supply of timber for their ships. Science and exploration also combined in the development of a set of technological devices that facilitated the efficient movement of people and things around the world. Practical charts of maritime navigation, the quadrant, accurate and robust timepieces, and new sorts of ships helped produce a science of exploration.

By 1650 most of the world's coastlines had been mapped, at a rudimentary level at least, and concerted efforts were underway to explore and map continental interiors. Although the majority of accounts came in the form of a topographical compendium, their geographical focus varied widely, ranging from descriptions of local areas up to continents and even the entire globe. In an attempt to make these texts useful to others, the Royal Society of London devised an agenda and method toward the standardization of exploration reports and the geographical scale of their enquiry. It preferred "regional surveys." Samuel Hartlib, the Prussian natural philosopher, promoted the use of regional surveys in the production of a "political anatomy" that organized geographical, economic, and social data. Meanwhile, Robert Boyle prepared a treatise to aid the regional surveyor, a eulogy to the inductive method, entitled *General Heads for the Natural History of a Country, Great or Small; Drawn Out for the Use of Travellers and Navigators* (1692). Boyle's text might be seen as a very early fieldwork manual.

The work of Carl Linnaeus gave a boost to international field studies, which both imitated his example and employed his classifications. Linnaeus botanized in Lapland, elsewhere in Scandinavia, Holland, France, and England. His students, or disciples as he called them, applied his binomial nomenclature to the world beyond Europe. From 1745 to 1792 nineteen of them left on voyages of discovery to, among other places, Australia and the Pacific, Siberia, Senegal, the Americas, the Arabian peninsula, the Ottoman Empire, and Africa. A series of other significant scientific expeditions of continental interiors took place during the eighteenth century. Mark Catesby and later John Bartram and his son William explored the American East Coast. Like Catesby before him, John Bartram made a good trade in supplying European natural history enthusiasts with North American specimens. Catesby and William and John Bartram, the latter acting as the King's Botanist in North America, also wrote and published influential natural histories of the Carolinas, Georgia, Florida, Pennsylvania, and the Bahamas. Many others continued to work in this tradition, culminating in the famous western territorial expedition of Meriwether Lewis and William Clark in the first decade of the nineteenth century.

Under French leadership, two international scientific teams set out in the 1730s to resolve the debate over the shape of the globe. One team, led by Pierre de Maupertuis and including Anders Celsuis, went to Lapland, the second team, led by Louis Godin and Charles Marie de Lacondamine, to Peru, to measure the length of a degree along the meridian. Their extensive collection of a wide range of measurements contributed to international scientific knowledge of the regions. At the very end of the century Alexander von Humboldt and his companion Aimé-Jacques-Alexandre Bonpland traveled through South America, accumulating enough material for thirty published volumes. Using more than four dozen measuring instruments, including chronometers, an achromatic telescope, sextants, compasses, barometers, thermometers, rain gauges, and theodolites, the two men set a new standard for regional scientific study.



Chronometer used on James Cook's second voyage, 1772

In particular, they pioneered the "isomap," the cartographic method for the delineation of comparative natural features.

Another landmark voyage of exploration was that of the HMS *Endeavour,* captained by James Cook. From 1768 to 1771 Cook traveled to the Pacific accompanied by a group of naturalists including Joseph Banks, the founder of the Royal Botanic Gardens at Kew, and Daniel Carl Solander, one of Linnaeus's foremost students. The first voyage's main objective was to observe from Tahiti the transit of Venus across the face of the sun. Although part of a broader international astronomical enterprise, the voyages played an important role in the introduction to Europe of the natural histories of New Zealand and Australia.

Cook's orders included taking possession of any new lands that might benefit the British crown. Banks and Solander's involvement in Cook's conquest of Australasia therefore enrolled naturalists as agents of the European imperial endeavor. It became commonplace for expeditions organized by the military to include men of science to assess the value of newly discovered lands and collect new species of plants and animals. These and others involved in the development of European colonial rule in the eighteenth and nineteenth centuries brought a wide array of foreign specimens back to their respective countries, feeding the growth of botanical and zoological gardens, natural history museums, and the trade in exotic plants. This association also benefited the development of the sciences. For instance, Charles Darwin's participation in the British Admiralty's hydrological survey of the waters around South America on the HMS *Beagle* was fundamental to the development of his theory of natural selection.

The study of ethnology also grew out of the close relations between science and empire in the nineteenth century. Although European traders had come into contact with different cultures for centuries, colonial expansion brought with it a heightened impetus to study aboriginal peoples, before their eradication by "civilization." The emerging sciences of anthropology and ethnology developed standardized methods for the measurement of the human body, termed "anthropometry." Nineteenth-century advances in photography made further important contributions to this effort. British colonial governmental officials carried out comprehensive photographic surveys of the peoples of India in the 1860s, and in Africa in the 1890s.

The university was an important site for the furthering of fieldwork as an integral aspect of science from at least the sixteenth century. From around 1525, university physic gardens introduced medical students to herbs as living plants rather than only as dried herbarium specimens. The lack of such a garden in Bologna forced the University's instructor in *medicina practica,* Luca Ghini, to take his charges into the countryside in search of herbs. Students of Ghini later led extended expeditions during university vacations that transformed into more general lectures on natural history. This practice spread to France in the 1550s and to Sweden, Denmark, England, and Scotland by 1650. London's Society of Apothecaries was the most persistent promoter of the field excursion as a necessary aspect of medical training. Its expeditions into the English countryside occurred for 214 years without a break, stopping in the nineteenth century only because it took so long to get beyond the sprawling metropolis.

Education in field study for medical students carried over into other scientific disciplines in the eighteenth and nineteenth centuries. It became increasingly common for botany and geology students at the European universities to undertake fieldwork as part of their study. This tradition was introduced to the United States by Louis Agassiz and Spencer Fullerton Baird, who pioneered formal field teaching at Harvard University and Dickinson College, Pennsylvania, respectively. Students benefited from the proliferation of inexpensive field equipment: guidebooks with directions for taking notes, collecting and preserving specimens, and formulating a collection; tools like specially designed and reasonably priced hammers, geological maps, and "botany boxes," with tightly fitting lids and carrying straps; nets for entomologists; and guns and cameras (though these required a heavier outlay) for zoologists. Easy access to field equipment contributed greatly to the widespread enthusiasm for field study in Europe and North America in the nineteenth century. Women, children, and artisans, as much as university-educated middle-and upper-class gentleman, participated.

The establishment of anthropology and geography as discrete university disciplines at the very end of the nineteenth century extended the close connection between a scientific education and field study. Practitioners in both fields placed in situ study at the center of their disciplines. More generally, academic science began to fragment into increasingly specialized sub-disciplines, and even the largest expeditions started to limit themselves to particular tasks. For instance, while Felix Andries Vening Meinesz surveyed marine gravity on world-ranging submarines, Jacob Clay and Robert Millikan circled the globe measuring cosmic rays at various altitudes, latitudes, and depths; while Jean Abraham Chrétien Oudemans produced geographical maps of the Dutch East Indies, others made magnetic measurements and took soundings of coastal waters.

Exploration and fieldwork declined in importance during the twentieth century. Automated data-collection devices such as satellites, self-recording weather stations, and seismometers reduced the role of the human observer. Meanwhile, exploration became increasingly driven by the agendas of multinational corporations scouting for new reserves of natural resources such as oil and gas. Notable exceptions to this rule were the mapping and scientific exploration of Antarctica and the sea floor.

The high latitudes of Antarctica made it of special interest for geophysical studies. Cooperative "Polar Years" were organized by geophysicists in 1882–1883 and 1932–1933. Mapping of the continent continued after World War II by nations interested in staking claims on the landmass. However, in 1957–1958 the International Council of Scientific Unions implemented the third Polar Year, formalized as the International Geophysical Year (IGY). The success of the IGY prompted the creation of the Special (changed later to Scientific) Committee on Antarctic Research (SCAR) in 1958. This led indirectly to the signing of the 1959 Antarctic Treaty, setting the continent aside for peaceful, international, and scientific purposes. However, despite the best efforts of SCAR, Antarctica remains the one continental landmass not yet comprehensively mapped by fieldworkers working on the ground.

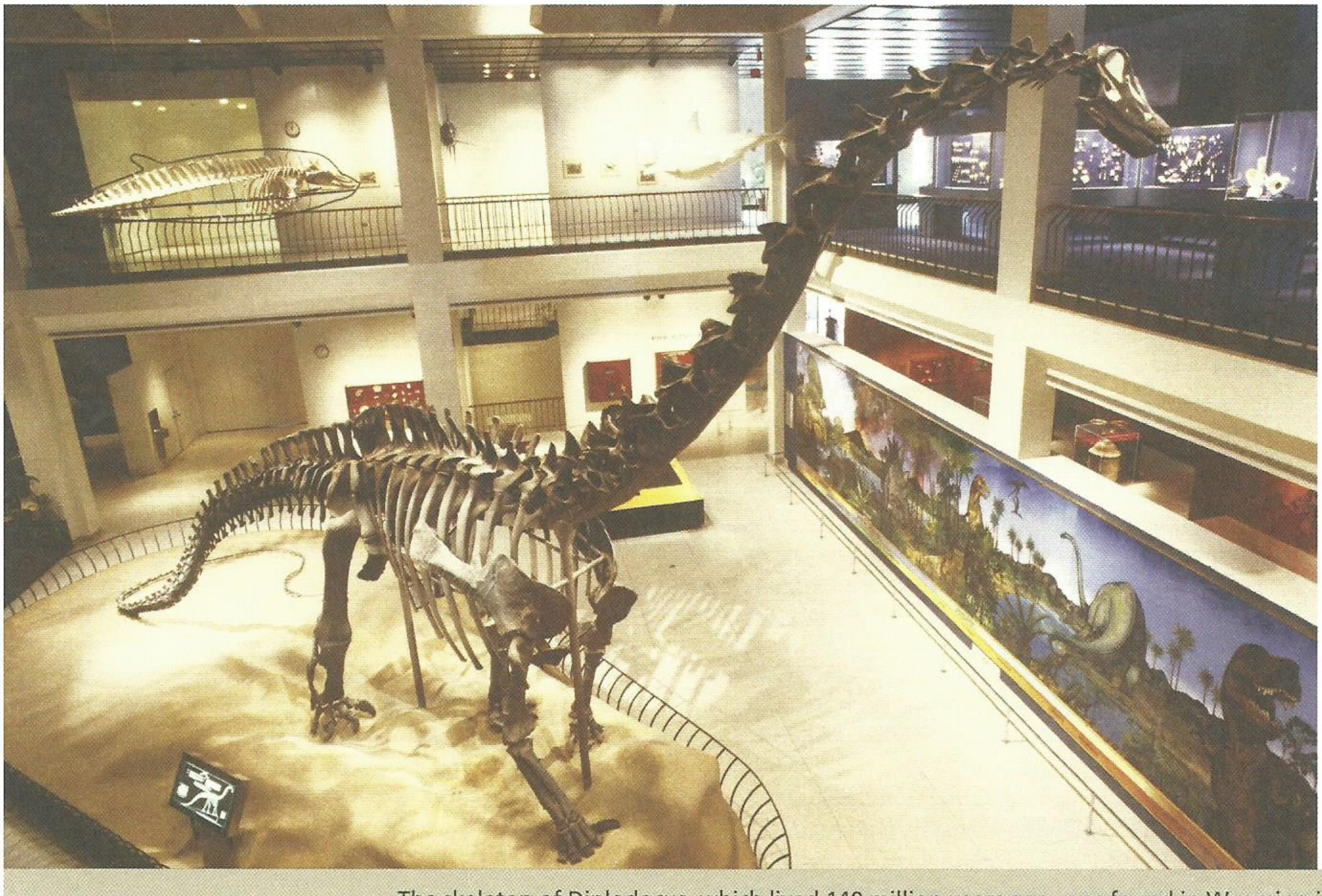
Simon Naylor

FOSSIL. Until the end of the eighteenth century, scholars could not decide whether fossils were the traces of dead creatures. For every fossil that clearly resembled a living animal, they found others unlike anything currently living. When minerals were believed to grow in the earth, and when spontaneous generation remained a serious hypothesis, many people assumed that fossils had grown in situ. In 1726, in a notorious example, Johann Beringer, a member of the faculty of medicine at the University of Würzburg, published a book full of illustrations of curiously shaped stones found in the region. He described them as the handiwork of God. They turned out to be the handiwork of jealous colleagues who had planted them as a hoax.

In the early nineteenth century, paleontology began to emerge as a subfield of geology. From the point of view of geologists, fossils were chiefly useful for identifying strata. Geologists concentrated on the fossils plentiful enough to serve this function, and so spent most of their time classifying marine invertebrate species. Questions that thrilled a wider public about the meaning of fossils and the history of life on earth were of limited interest to paleontologists. They have, however, loomed large in the public image of geology.

When Georges Cuvier and his followers excavated bones and reconstructed giant beasts such as the mammoth or the ichthyosaurus, they showed to almost everyone's satisfaction that some species had become extinct. While fossil marine bivalves might be thought to have living representatives in some distant ocean, no one expected to find an ichthyosaurus in a remote part of the world. How and why extinction has occurred was to generate much speculation in both scientific and religious circles.

Meanwhile, the search for fossils of extinct vertebrates had started. In 1824, the English geologist William Buckland published the first paper describing a dinosaur. In 1842, another Englishman, Richard Owen, coined the term for these creatures. Almost immediately, dinosaurs captured the place in the public imagination they retain to this day. Professional fossil collectors mounted expeditions to likely sites. At the beginning of the twentieth century, the steel magnate Andrew Carnegie, reading of a discovery of a giant dinosaur in Wyoming, dispatched a team to secure it for his new museum in Pittsburgh. After various adventures, the bones of *Diplodocus carnegii* arrived. So spectacular was



The skeleton of Diplodocus, which lived 140 million years ago, was found in Wyoming in 1902 and is now displayed at the Museum of Natural History in Houston, Texas the creature when reconstructed that national museums throughout the world considered themselves incomplete without one. Plaster casts of Carnegie's dinosaur can now be seen in England, France, Austria, Russia, Germany, Spain, Argentina, and Mexico.

Charles Darwin admitted in his *Origin of Species* (1859) that the fossil record with its many gaps posed a severe problem for his theory. He resolved the problem by asserting that the record was incomplete. Nonetheless, his followers, including T. H. Huxley and O. C. Marsh, professor of vertebrate paleontology at Yale University, thought it important to try to trace ancestries for at least some species. They were particularly successful with the horse. For the public, though, the more important question remained the "missing link" between humans and their simian ancestors. The remains of Neanderthal man came to light in 1856, followed by Peking Man (1903) and Piltdown Man (1912), exposed as a hoax in 1953.

The ability of fossils to stimulate the imagination has not declined in recent years. In the late 1960s, a new debate started when two Americans, Robert Bakker and John Ostrom, suggested that dinosaurs were hot blooded and thus lively, not the slow-moving creatures that had been imagined. Just a little over a decade later, a group of American scientists led by Walter Alvarez suggested that dinosaurs had been killed off by an extraterrestrial object hitting the earth about sixty five million years ago. Most scientists now seem to agree. Another round of interest in fossils, sparked by the discovery that traces of DNA can be found in some fossils, inspired Stephen Spielberg's film *Jurassic Park*.

RACHEL LAUDAN

FOUNDATIONS. During the twentieth century, scientists' need for expensive experimental apparatus, large research teams, and international travel required diligent searches for funds that have been integral to setting research agendas. As Robert Kohler described the situation, "Assembling the material and human resources for doing research is no less a part of the creative process than doing experiments." Throughout the century, but particularly in the first half, foundations were central to that process.

The perpetual charitable trust as a legal entity intended to deliver a specific public benefit dates from the Elizabethan era. The general-purpose philanthropic foundation awaited the late-nineteenth-century elaboration of the nonprofit organization to give it a vehicle, and the capitalist accumulation of wealth to make it substantial. Philanthropically created foundations that support science are primarily a recent American phenomenon.

The first large foundation to support fundamental research was the Carnegie Institution of Washington, initially endowed by Andrew Carnegie with $10 million and enlarged with later gifts. The Institution hired scientists and created laboratories of its own and made numerous small grants to individual scientists and large ones to institutions, such as the Mt. Wilson Observatory and the National Research Council. Over the next three decades, American science benefited from other foundations as well: Robert Goddard's rocket experiments had support from the Carnegie Institution and the Guggenheim Foundation; Albert Einstein's visit to the United States in 1931 to collaborate with Robert Millikan was funded by the Oberlaender Trust; the China Foundation's fellowships sent Chinese geneticists and biologists abroad for advanced training. The Sauberán Foundation in Argentina helped to establish Nobel laureate Bernardo Houssay's Institute of Biology and Experimental Medicine in Buenos Aires in 1944. In the 1950s, the Nutrition Foundation provided fellowships for Central American food chemists to study in the United States.

The largest amount of money distributed in the first half of the twentieth century came from the cluster of philanthropies created by the Rockefeller fortune. Led by the Rockefeller Foundation, these philanthropies initiated programmatic giving that focused funding on particular institutions, disciplines, or problem areas, and relied heavily on knowledgeable program officers to make decisions about allocations. Rockefeller institution-building created or supported major research centers, including the Peking Union Medical College (founded in 1918), the Bohr Institute in Copenhagen (1921), the Mathematical Institute at Göttingen University (1926), the Palomar Observatory (1948), and public health institutes in Europe, the United States, and South America.

In specific fields, Rockefeller funding had significant effects. Support of physicists in the 1920s and 1930s aided in shifting the center of physics from Europe to the United States. The Rockefeller Foundation helped to create molecular biology, contributing approximately $25 million to the field from the 1930s through the 1950s.

Rockefeller philanthropies greatly expanded the role of the fellowship, both resident and traveling, as a means of shaping or even redirecting careers. In 1919, the Rockefeller Foundation began a twenty-year program run by the National Research Council, which at first supported physicists and chemists, but soon expanded to biologists and psychologists. The International Education Board (IEB), created in 1923, was the first Rockefeller philanthropy to focus on fellowships as a means of promoting science. These fellowships enabled young researchers to devote their time to their specialties during what was generally their period of greatest productivity.

After the IEB merged with the Rockefeller Foundation in 1928, the fellowship program became global, and assisted many scientists and organizations in less-developed regions. Alberto Hurtado became research director of Peru's Institute of Andean Biology in 1934 after holding a postdoctoral research fellowship from the Rockefeller Foundation at the University of Rochester. Over the next twenty years, the Foundation granted ten fellowships to Hurtado's staff to study abroad; combined with Rockefeller grants for instruments, this program made the Institute a global leader in physiology studies. Extended throughout Latin America, the fellowships of the Rockefeller Foundation, and similar fellowships offered by the John Simon Guggenheim Foundation, helped to reorient Latin American science from Europe to North America.

After World War II, the rapidly increasing scale of government-funded research induced the largest foundations, including the Rockefeller Foundation, to withdraw from general support of the natural sciences. Both the older and newer foundations turned to more specific and applied areas such as agriculture, population studies, and medicine. Particularly wealthy foundations such as the Wellcome Trust (1936) and the Nuffield Foundation (1943) in Britain, and the Howard Hughes Medical Institute (1953) in the United States, supported medicine.

Because foundations can focus on specific research areas and dispose of funds flexibly, their institutional form was adopted throughout the world in the latter part of the twentieth century, often by government initiative. The Merieux

Foundation (1967) supports research in biology and medicine in France; the Mario Negri Institute (1961) supports biomedical research in Italy; the interrelated Fundación Andes, Fundación Antorchas, and Vitae (Apoio à Cultura, Educação e Promoção Social) in Latin America (1985) and the Volkswagen Foundation (1961) in Germany give to higher education science research. A major example of government-created foundations that fund research is the Deutsche Bundesstiftung Umwelt, the largest foundation in Europe in the 1990s, established by the German government with the proceeds of the sale of a publically owned corporation. In the twentieth century, foundations became an integral element of the scientific enterprise, responsible for the founding or expansion of institutions, providing crucial support for the development of scientific careers, and aiding in the creation of new fields of science.

DARWIN STAPLETON

FRAUD. In 1981, then-Representative Albert Gore, Jr., began the hearings of the Investigations and Oversight Subcommittee of the House Science and Technology Committee. Cases of scientific misconduct had been disclosed at four major research centers in the 1980s; doubts about the integrity of American scientific research circulated. Gore wondered publicly if these cases were not "just the tip of the iceberg." Answering in the affirmative in 1982, William Broad and Nicholas Wade, well-regarded science journalists who had worked for both the *New York Times* and *Science,* published in their *Betrayers of the Truth* that scientific fraud was much commoner than anyone had believed.

Fraud is a particularly serious sin in science, whose whole purpose is supposed to be the pursuit of truth or knowledge. In the biomedical sciences in particular, a distressingly common pattern of misconduct seemed to be emerging. John Darsee, a cardiologist at Harvard Medical School, published over a hundred articles and abstracts between 1979 and 1981. After charges of fraud led to investigations in 1981, he retracted fifteen out of the twenty articles questioned. Other cases surfaced at the University of California at San Diego, the University of Pittsburgh, the Baylor College of Medicine, and the Massachusetts Institute of Technology. The latter became known as the Baltimore case because the senior author of the article allegedly containing a junior author's fraudulent data was David Baltimore, Nobel Prize winner and by then president of Rockefeller University. Although Baltimore himself was not suspected, his support of the junior author seemed ill advised. Eventually, in 1991, she was cleared of all wrongdoing, but by then the case had caused Baltimore's resignation from Rockefeller and widespread public concern.

The furor over the Baltimore case reflected growing suspicion about the practices of science. Broad and Wade had claimed that fraud was endemic to the scientific enterprise. The supposed perpetrators listed in their book included some of science's most lustrous names. Ptolemy, they charged, invented astronomical measurements; Galileo reported results too perfect to be credible; Isaac Newton fudged data; John Dalton described experiments he probably never performed; Gregor Mendel produced statistical results too good to be true; and Robert

Reconstruction of Piltdown man from the jaw fragments (in brown) found in Sussex around 1912. Interpreted as the link between man and apes, in fact (as was shown in 1953), the human skull and ape jaw belonged to different individuals.

Millikan, awarded the Nobel Prize in 1923 for measuring the charge on the electron, had selected only the readings that suited him.

Far from being disinterested seekers after truth, Broad and Wade argued, scientists were as ambitious and anxious for recognition as any other professionals. They rarely replicated experiments, supposedly one of the best checks on fraud, because they received no credit for doing so. And in the face of charges of fraud or threats of regulation from outside, the scientific community drew together instead of subjecting their colleagues to investigation.

Scientists, government officials, and historians undertook serious studies of the problem. They quickly discovered the difficulty of defining fraud. Faking data with the intent to deceive others (the motive, according to most scientists, behind the planting of the Piltdown skull) was clearly wrong. But what to make of the practices identified in the nineteenth century by the computer pioneer Charles Babbage: forging (reporting observations that had never been made), trimming (working with data to make them look better), and cooking (choosing the data that best fit the theory under test)? On occasion depending on the choice of the appropriate statistical methods, trimming or cooking might be appropriate. What about thought experiments, experiments that took place only in the scientist's head? And preparing a streamlined and cleaned-up version of research for publication, although it could involve fraud, was also in most cases unproblematic scientific practice. Historians of science believed that many of the historical cases adduced by Broad and Wade fell in a benign category.

In any case, the American scientific community had not been prepared to deal with fraud. Techniques for detecting it were rudimentary. "Whistle blowers," who were as likely to suffer as the scientists they charged, brought most cases to light. Procedures for handling cases once detected did not exist. In 1985, Congress passed the Health Research Extension Act. It included important provisions concerning fraud: institutions receiving federal money had to establish administrative processes to review reports of fraud; and the National Institutes of Health had to establish a process to respond to their findings. It took five years to draft and discuss guidelines. In 1989, these were published in the Federal Register. To avoid emphasizing questions of motive, the term "fraud," defined in law as intent to deceive, did not appear. Instead misconduct was defined as "fabrication, falsification, plagiarism, or other practices that seriously deviate from those that are commonly accepted within the scientific community for proposing, conducting and reporting research."

The guidelines created considerable controversy. Many scientists wanted the ruling confined to fabrication, falsification, and plagiarism rather than opening the door to the policing of other practices that, although dubious morally (e.g., sexual harassment), were not specific to the scientific enterprise. Efforts to set up a system to deal with misconduct continued. In 1992, the Public Health Service set up the Office of Research Integrity. Over the next five years it received approximately a thousand allegations of misconduct. It investigated 150 of these and found against the researchers in about half of them. Some of its conclusions, most spectacularly in the Baltimore case, were reversed.

Although the problem of fraud emerged in the United States and seems to have been most intense there, other countries with substantial programs of scientific research, including Great Britain, Japan, Germany, France, and Australia, have all put in place procedures to detect and regulate misconduct in science. In an enterprise funded by public money, it is not surprising that governments set up systems for assuring accountability, but that they did without them for so long.

Rachel Laudan